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JSC-09256

NASA TECHNICAL MEMORANDUM

NASA TM X-58158
April 1975

PROCEEDINGS OF THE 1974 LYNDON B. JOHNSON

SPACE CENTER WHEAT-YIELD CONFERENCE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

LYNDON B. JOHNSON SPACE CENTER

HOUSTON, TEXAS 77058

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16. Abstract

This document contains the proceedings of the 1974 Lyndon B. Johnson Space Center Wheat-Yield Conference. Subjects covered include plans for wheat/climate-change research; world agricultural weather watch; application of crop and weather statistics in real-time decisionmaking; wheat-growth/environment/yield relationships; weather/crop modeling in the U.S. Department of Agriculture Economic Research Service; winter wheat: a model for forage and grain; a model of global wheat productivity: U.S. spring wheat; wheat-yield estimates based on weather: research and applications in Canada; a proposed technique for adjustment of yield prediction for fertilizer use; a climatological assessment of evaporation; use of ERTS-1 for determining growth and predicting disease severity in wheat; percent green as an indicator of biomass and phase development; canopy modeling for relating scene attributes to reflectance; modeling the interaction of meteorological variables and leaf area index on yield; application of remote sensing to estimation of evapotranspiration; and modeling corn growth by incorporating soil and climate factors.

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PROCEEDINGS OF THE 1974 LYNDON B. JOHNSON

SPACE CENTER WHEAT-YIELD CONFERENCE

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CONTENTS

1. INTRODUCTION

By David E. Pitts[*] and Gerald L. Barger[†]

The 1974 Wheat-Yield Conference was conducted at the NASA Lyndon B. Johnson Space Center. The purpose of the 2-day conference was to determine the state of the art of wheat-yield forecasting and the feasibility of incorporating remote sensing into this forecasting. The major consideration was to formulate a common approach to wheat-yield forecasting, primarily using conventional meteorological measurements, which can later include the various applications of remote sensing. The possibility of combining remote sensing with available surface meteorological observations — that is, those observations that are available on worldwide teletype communication lines — is being studied. Primarily, NASA is interested in testing developing technology in remote sensing as a possible means of recognizing crop conditions and estimating crop production.

For several years, the Earth Resources Program at NASA and the general scientific community have been using remote-sensing programs to identify simple features such as crops and crop types and to estimate acreage. However, remote sensing has not been widely used to estimate actual crop productivity. Claims of detecting crop stress factors with remote sensing have usually exceeded actual accomplishments. The current effort is to determine the developmental state of crop modeling in terms of production assessment to discover the applicability of meteorological satellites and Earth resources technology satellite systems. The use of remote-sensing techniques will augment rather than exclude the use of conventional data sources. The NASA effort will be in cooperation with other agencies that assess agricultural production, certainly the U.S. Department of Agriculture and the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce.

The 1974 NASA Lyndon B. Johnson Space Center Wheat-Yield Conference was attended by agronomists, meteorologists, statisticians, and remote-sensing experts chosen to present their recent contributions in the area of crop modeling. Each participant presented a discussion of work in his area of specialization and related his methodology to crop modeling. This cooperation among the representatives of different agencies and institutions promises to be the basis for whatever success may be achieved in monitoring crop development and estimating grain production. The many problems encountered within these various disciplines were not solved in one conference; however, the chances for valuable results in the future are good.

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2. PLANS FOR WHEAT/CLIMATE-CHANGE RESEARCH

By Clarence Sakamoto*

The Environmental Study Service Center at Auburn, Alabama, which began in July 1973, is still in a formative stage. The project that is concerned with climatic change began only a few months ago. This project is based on the concern by the Department of Transportation (DOT) that aircraft operating in the stratosphere for several years might alter the global radiation balance. If this alteration occurs, the question arises as to the agronomic implication. This project is concerned especially with the effect of agronomic change on nondomestic wheat. The applicable areas include the following five countries: the U.S.S.R., Argentina, China, Australia, and India. The past 3 months have included a familiarization study to answer the following questions: Where are the wheat-growing areas? What is the climatic situation? How long is the growing season? When does frost first occur? This information will later form the basis for modeling inputs.

This project is a 1-year study that began in October 1973. The plans for this study involve essentially two approaches. The first approach to be investigated, the phenological approach, is a search for information that might reveal what happened in archeological times to the wheat belt and to the growing season. Sometimes history can reveal much about the future. An eminent Chinese climatologist has described what happened climatologically in China from 5000 years ago to the present. The discussion, containing some of the information that he has found in diaries, histories, and oracle bones, reveals much about how cereal crops are affected by climatic changes.

The second approach, which will depend on data availability, is the statistical approach. Models that have been developed for nondomestic areas will be investigated to determine what occurs during selected temperature and precipitation changes. Another area of concentration in this modeling task is clustering, which might be described as a mathematical approach to study groups and areas that are similar. Clustering is another method of attempting to find climatic analogs. If wheat-yield models were available, this clustering technique would isolate similar areas in which unique models could be applied. A tendency exists to accept models that are already in the literature to estimate wheat yields; however, a model does not work well in areas other than those for which it was designed. Clustering is a relatively new area and is related in some respects to principal component analysis.

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A familiarization study has been published in a quarterly report to DOT. Some yield data and climatic information are available from Asheville, North Carolina. The Atmospheric Sciences Library in Washington, D.C., is the depository for foreign climatic information.

PEARL: I am interested in the time frame that you were working with in this familiarization study with these countries. We are in a similar familiarization mode now; thus, I would like to know how long you took for your familiarization studies?

SAKAMOTO: Before we started this particular project, we were not sure where the wheat was grown in the world. The past 3 months have been spent studying these wheat areas. We have maps describing the growing season, frost indications, and soils. These maps will serve as a basic reference. This familiarization study, which began in October 1973, has been completed as far as I am concerned.

PARK: Have you looked into the defense literature on intercontinental nuclear war data? Numerous work was done by the National Oceanic and Atmospheric Administration (NOAA), who studied the climatic effect of Krakatoa, the enormous volcano. The NOAA modeled the effect in a way that would study particle sizes of nuclear weapons in the stratosphere. Some data exist on climatic results of that type intrusion into the atmosphere. The U.S. Army Corps of Engineers has completed several studies that are related to the military environment in different countries and has studied clustering. However, the radionuclide exchange in the stratosphere is probably the most important and thoroughly studied analog to your problem.

SAKAMOTO: Thank you very much. I might add that several people are involved in this climatic change program with DOT. They are especially concerned with stratospheric problems. I am completely divorced from this area; however, I appreciate your comments. As you might imagine, this situation is very involved and complex. When this study is completed from DOT, approximately five or six monographs will be concerned with this project. Each monograph probably will be 2 to 3 inches thick.

KAN: I wonder what aspects you involved in clustering and in what directions you are looking into this problem?

SAKAMOTO: To find specific information from different countries, for example, the U.S.S.R., has been difficult. I am seeking yield data from that area. I have not been able to obtain a complete set of data. In attempting to work with this clustering problem, one approach is to determine areas that have similar situations or climatic analogs. Having accomplished this task, we could utilize areas that have readily available information and could apply their data and prediction model to the U.S.S.R., for example. This application method is our primary interest in terms of clustering.

PITTS: The clustering that is being used at Purdue University, the Environmental Research Institute of Michigan, the University of California, Lyndon B. Johnson Space Center (JSC), and other areas is primarily for classification of remote-sensing data — that is, using multispectral scanner data, identifying areas with training fields, clustering these data, and then recognizing and identifying other features based on these data. In the Atmospheric Science Library that you referred to part of NOAA?

SAKAMOTO: Yes.

PITTS: Is your work with DOT part of the Climatic Impact Assessment Program?

SAKAMOTO: Yes.

PITTS: What is your time schedule?

SAKAMOTO: This project essentially terminates December 31, 1974.

NEWMAN: You spoke of clustering and analog phenology, but you never mentioned Nuttonson's work. Are you using his input?

SAKAMOTO: I am familiar with Nuttonson's work, and it might be part of the input in this study. I used his work as a reference in my familiarization study.

NEWMAN: He is still active; however, much of his work was done 10 to 20 years ago.

BARGER: By making world-yield data, weather data, and other accumulated data available at JSC, NASA is hoping to help solve this data collection problem through internal efforts and university contractors.

3. WORLD AGRICULTURAL WEATHER WATCH

By Richard Felch*

Interest in crop production and weather influences is incisive. For the first time in many years, the National Oceanic and Atmospheric Administration is concerned with making world weather information useful to agriculture. Through the world weather network and meteorological services of the various countries, much information is available. In the fall of 1973, action was begun to provide as much of the world weather data as possible in a reasonable form for agricultural operations. From this initial effort, a two-phase program is being developed to make this information available.

The first phase of the program, which is partially completed, will be to make available a map of the monthly CLIMAT data from the various agricultural producing countries. Through the auspices of the World Meteorological Organization (WMO), at the conclusion of each month each country will prepare a specified summary of pressure, temperature, and precipitation data. These data will be placed on the world weather wires and will be available to everyone. This information will be published in the Weekly Weather and Crop Bulletin on four separate maps during the month following the observations.

Actual monthly precipitation will be depicted on the first map (figs. 3-1(a), 3-2(a), and 3-3(a)). This information is very important for crop production, especially wheat, because many of the important wheat-producing areas of the world are in low-to-moderate rainfall areas. Monthly precipitation departures and the percentage of normal precipitation will be shown on the second map (figs. 3-1(b), 3-2(b), and 3-3(b)). Average monthly temperature will be illustrated on the third map (figs. 3-1(c), 3-2(c), and 3-3(c)). Monthly temperature departures will be listed on the fourth map (figs. 3-1(d), 3-2(d), and 3-3(d)). Areas that are warmer or cooler than normal will be indicated on this map. An average temperature for the month does not signify much; however, the temperature departures can indicate how the growing season is progressing and whether the temperature is warmer or cooler than usual.

The second phase of the program, which will be much more difficult in terms of data handling but much easier in terms of effort, will be to collect the daily surface observations that arrive from the world weather wires, to store this information, and to summarize it each week. Important agricultural areas will be selected on a subregional basis, and an average value will be provided for each region.

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*National Oceanic and Atmospheric Administration, National Weather Service, Washington, D.C.

The major problem is that although precipitation is one of the key figures, it is very difficult to obtain. Of the daily surface observations coming over the world weather wires, precipitation is considered an extra group. Some countries send this information, whereas some do not. Some countries send it once daily; some send it four times daily. Thus, the programing problems involved in attempting to handle this information by computer are rather exhaustive, and a full-time programer will be required to handle this information on an extended basis.

Certain parts of the world have fairly good coverage. Presently, the U.S.S.R. is one of the most reliable reporting areas. Data are received regularly from approximately 200 stations. Good data are received from the United Kingdom and Ireland. Several Mediterranean countries are very reliable. West Africa is a very reliable source of information. Surprisingly, virtually no information comes from eastern and southern Africa; thus, these areas are a problem. Data receipt from Brazil and Argentina is reasonable, but almost no data are received from the rest of South America. Virtually no data come from Australia and New Zealand, which is rather surprising. Information is nonexistent from many of the European countries, particularly Germany.

Initially, the approach will be to correspond with people from the Communications Division of the National Weather Service who are working with other worldwide communications offices. If necessary, the WMO can supply the data because all these countries have agreed to provide certain information; however, this method would require several months.

Map-form weather data for selected areas of the world will be available for the parameters in the Weekly Weather and Crop Bulletin. Hopefully, the 6-month running total will be available. The weekly data will be available 6 to 12 months later. This information will be collected and summarized by computer. Most of the actual data plotting will be done by computer; however, map analysis will be done manually because of an insufficient number of data points. This information will be available in printed output form, and tapes should be available for anyone who would want this information.

CHIN CHOY: The International Biological Program is undertaking a cotton model that requires radiometric data, preferably solar radiation. Does any plan exist to incorporate these data into the data that you are compiling?

FELCH: Presently, this information is not available in the monthly CLIMAT data. The information could be requested, but it is the type of request that the WMO would have to act on; thus, 2 to 3 years would elapse before it would be available. Select stations might send the daily surface information as an extra group if they have it. The precipitation given in the daily surface information is considered an extra group. Some of these countries will send these extra groups, but the computer will often cut off the end of the message because the computer is programed to reliably recognize specific groups that are required every day. Although this information is being recorded on a particular station or country, it does not always reach us.

SMITH: Very early in your presentation, you mentioned in your monthly temperature summary that you were going to relate temperature deviations rather than the mean. Did I understand correctly?

FELCH: Yes.

SMITH: Many of the stochastic model techniques that are now available require a mean. Do you think that decision is wise?

FELCH: Do you mean on a monthly basis?

SMITH: Yes.

FELCH: If you feel the effort is worthwhile, no problem exists.

SMITH: The absolute value is important.

FELCH: The other potential problem with our approach is that, as it stands now, these maps will have been analyzed; therefore, isolines will appear on the maps.

SMITH: People will want the mean.

BARGER: Means are available in the published World Weather Records for some of the same stations. You might find the means there.

SMITH: My point is just so the means are available.

FELCH: No additional difficulty exists in plotting actual temperatures because we are allowing the computer to do all the work. The main concern was to keep the published material to a reasonable limit to handle it without starting an entirely new publication.

PARK: I have two questions. Considering the importance of surface windspeeds on plants, wouldn't it be desirable to have these when a serious temperature departure occurs?

FELCH: We will not have available this type of information via the monthly report. The monthly CLIMAT message will provide the average surface pressure, the average sea-level pressure, the total precipitation, the number of days having a precipitation greater than 1 millimeter, and the mean temperature. In the precipitation group, a quintile group is given in terms of statistical probability in which the total falls.

PARK: I would also like to ask how you convert your precipitation measurements into map form. What kind of modeling do you use to generalize the precipitation into information?

FELCH: Our present intention is to use as many data points as we can obtain. A gridscale could be done by computer because it will already be in the computer. We will then try to analyze the data points by hand, based on the values received and on our knowledge of geography. We will attempt to give some meaning to the isolines. If we allow the computer go with the data scatter, we are going to encounter some real problems. People who will be working with this type of information should place the actual data values on the map and run the isolines on top.

BARGER: Will the individual data items be available on the tape? You are talking about publishing weekly averages, but can you provide more detailed daily extremes to those who are running the program?

FELCH: Yes, I thought I made that point clear. Any data we collect to obtain the value that we publish will be readily available. Once we begin publishing this information, to answer these kinds of inquiries will be a full-time job. For example, everyone in the U.S. Department of Agriculture who is concerned with what has happened can be provided with a complete update of the precipitation for the month.

KAN: Are those persons working in wheat-yield modeling, whatever type of modeling, going to require statistical information other than the mean or the departures from the mean of temperatures and precipitation? Present models may not accommodate all these parameters, but I would also like to have those parameters.

FELCH: The data to be provided in the Weekly Weather and Crop Bulletin
              will be very limited in terms of what you can include in modeling.
              On the monthly groups, we are going to have only one number. No
              indication will be given of what the extremes were during the
              month. Thus, problems exist in the system, but at least the mean
              will give some indication.

ROBERTSON: I would like to make one comment about the precipitation group in
              the synoptic code. You mentioned the problem of missing reports.
              We have been using these worldwide synoptic reports for approxi-
              mately 5 to 6 months. I would like to emphasize that precipitation
              is probably the weakest part of the entire report from an agricul-
              tural standpoint. To solve the problem, a mandatory group in the
              synoptic code should show the accumulated rainfall from the begin-
              ning of the year. If a storm occurs and the power goes off or if
              the observer cannot make an observation exactly at that time, the
              report is missing. Thus, the very information that we want record-
              ed is the very information that is missing. If we had an accumu-
              lated value in the report every 6 hours, at least we would have an
              accumulation of the rainfall. We could determine the past rainfall
              for any period if the sum reports were there; even one report a
              week would be quite ample for the purpose. We inventoried these
              synoptic codes that are being included. Approximately 5000 sta-
              tions in the Northern Hemisphere report, but we only receive
              approximately 1400 of these reports. What about reports from the
              People's Republic of China?

FELCH: Presently, we are not receiving any CLIMAT data from China on
              the monthly summaries, but we are apparently receiving daily
              synoptic reports. Some data exist because our maps are coming
              through with data on them.

ROBERTSON: Do you receive rainfall data?

FELCH: I do not specifically know the status of rainfall data that concern
              China.

ROBERTSON: We have checked with Hong Kong; they report rainfall. However,
              our tapes show no rainfall there. Rainfall information is being
              deleted, but I can not discover who is responsible.

FELCH: For those who have not worked with the world weather wire program,
              I think this discussion will give you some appreciation of the
              problems that you will encounter from a modeling viewpoint in
              terms of data receipt.

ROBERTSON: Synoptic reports are received every 6 hours, four times a day.

FELCH: This receipt is only from some countries.

ROBERTSON: Well, yes. These time periods are the regulations.

FELCH: Okay.

ROBERTSON: How are these reports handled? Are tapes available? Could I
               order copies of those tapes daily or once weekly?

FELCH: I think the reports are dumped onto a tape and kept for 24 hours.

ROBERTSON: These reports are not our type?

FELCH: I do not think the reports are our kind. We can check into this
               matter.

ROBERTSON: That is what your new program is aimed at, isn't it?

FELCH: Yes. We will have selected data on this synoptic report such as
               the temperature and precipitation, which will be put onto a tape.
               We will maintain a file of these tapes. If somebody wants details
               that we could not previously provide, we can locate them in the
               file.

ROBERTSON: Because of the poor quality of the rainfall observations, we are
               considering the entire report: cloudiness, present weather, past
               weather, and so forth. You have to determine whether the general
               weather of an area was wet or dry from facts other than actual
               rainfall; thus, the entire report is important.

PHINNEY: Last summer when we looked at how they stored that tape, it was
               going onto a disk, and, depending on the volume of data as it
               rotated through, you would lose data. The data receipt was approx-
               imately 24 hours. Once you reach the weekly stage, are you going
               to make any effort to incorporate a moisture factor — for example,
               either the crop moisture index or the Palmer drought index — and
               to adapt it to a worldwide coverage?

FELCH: I am not quite that far advanced, but I think that information
               will be included later.

PHINNEY: We have been discussing about generalizing that model for years.

FELCH: In the Palmer index that he is talking about, we have to have
               some knowledge of such factors as soil characteristics, deficit
               soil profiles, water-holding capacity, and soil types. On the
               weekly information, which will require collecting the daily obser-
               vation, we are at the initial planning stages. For those of you
               who are interested in historical data, an Environmental Data Serv-
               ice (EDS) publication, the Monthly Climatic Data for the World,
               will provide much of the same information found in the Weekly
               Weather and Crop Bulletin. The only problem with the EDS publica-
               tion is the 6- to 7-month lag time. However, our summary can keep
               you reasonably current.

PITTS: Fortunately, I do not think you have the problem that the Global
            Atmospheric Research Program has concerning the effect of the ocean
            areas. Have you looked forward to phase 2 in the weekly data
            and how you might manage that in the Weekly Weather and Crop
            Bulletin?

FELCH: Phase 2 will be mainly a programing problem — that is, writing
            a program capable of synthesizing all these data, including the
            exceptions. Six WMO regions exist. Different regions have
            slightly different formats for their individual countries, and
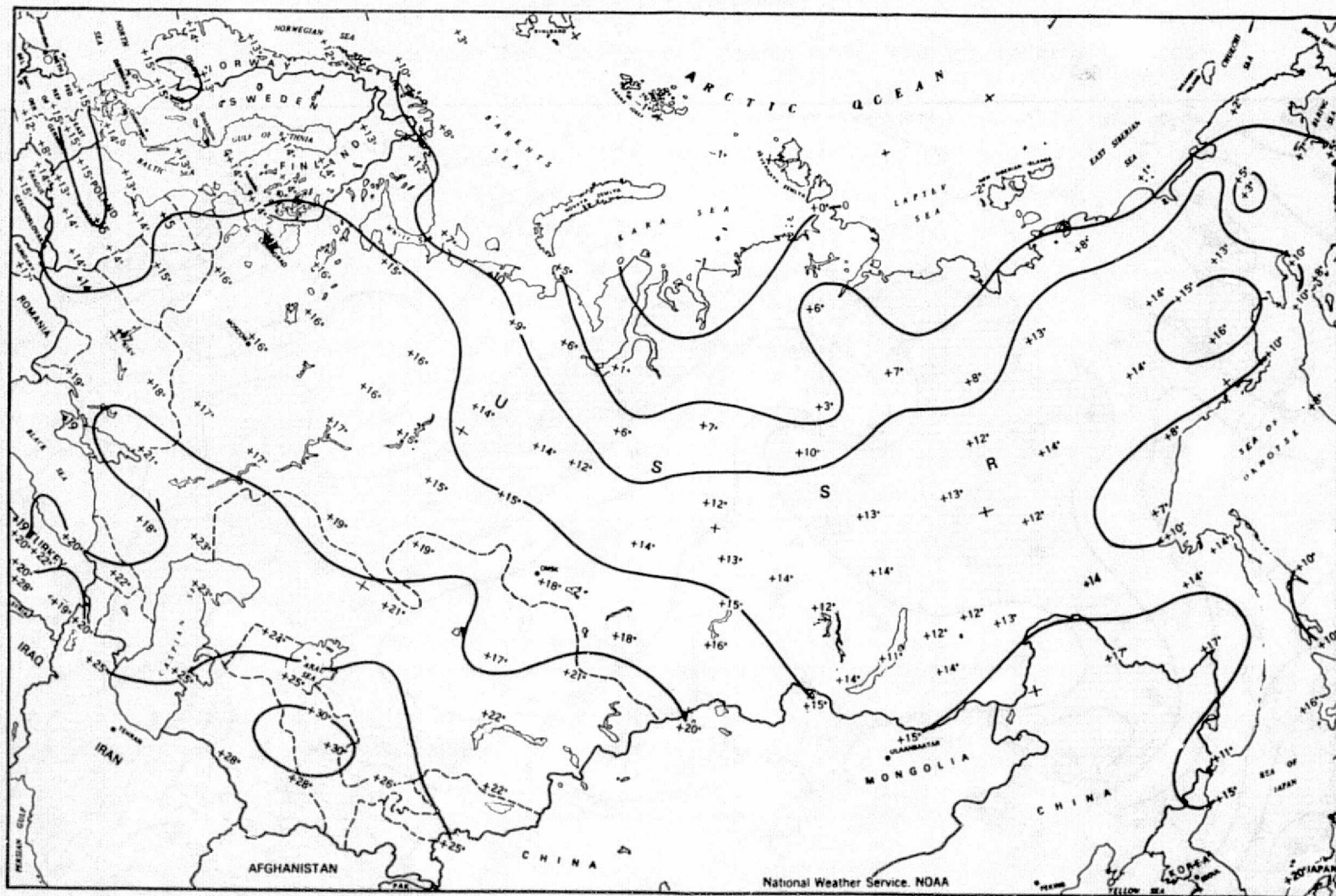   the individual countries have variations.
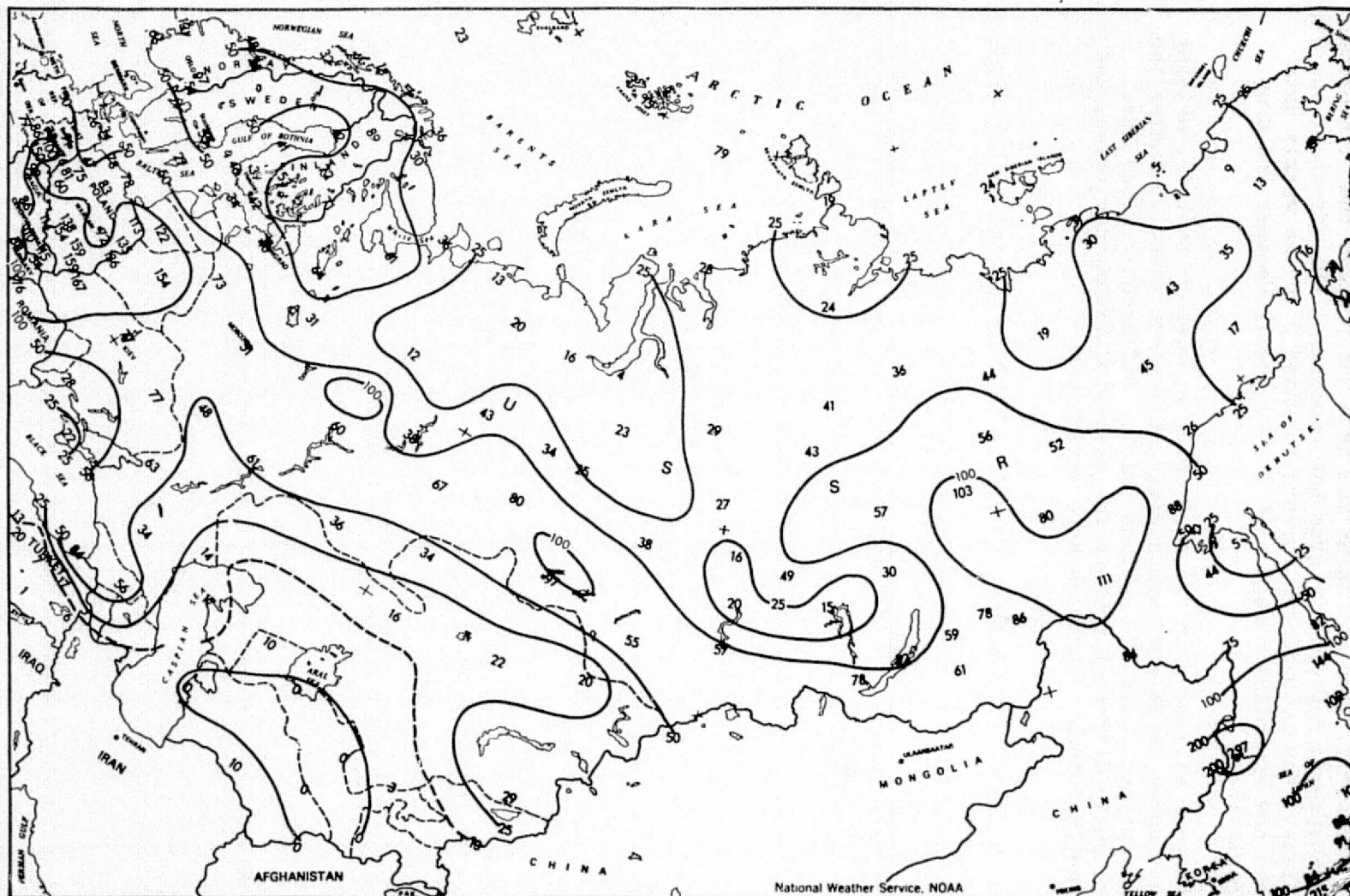
(a) Total precipitation in millimeters.

Figure 3-1.- Weather conditions for June 1974 in the U.S.S.R. (reproduced from the Weekly Weather and Crop Bulletin).
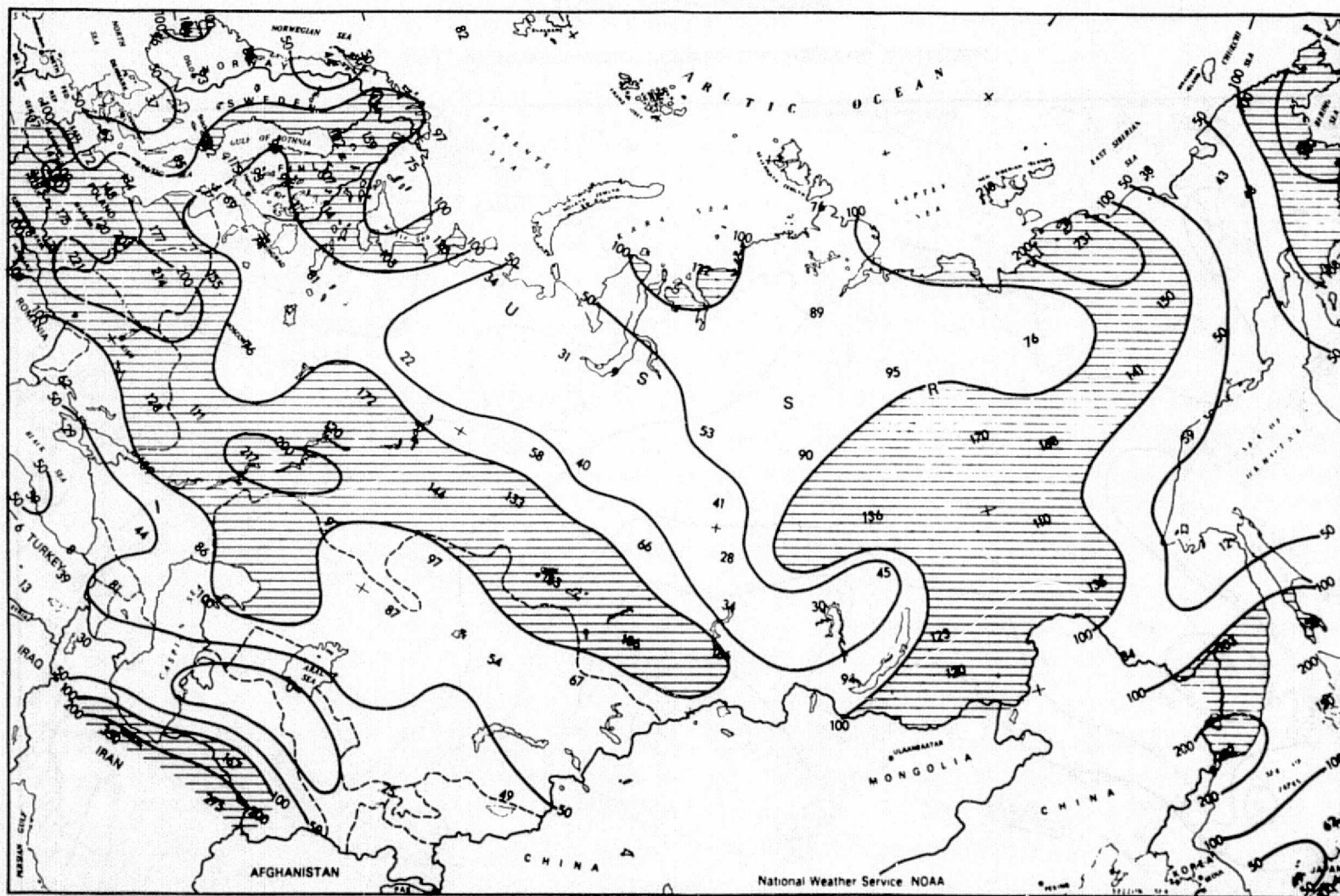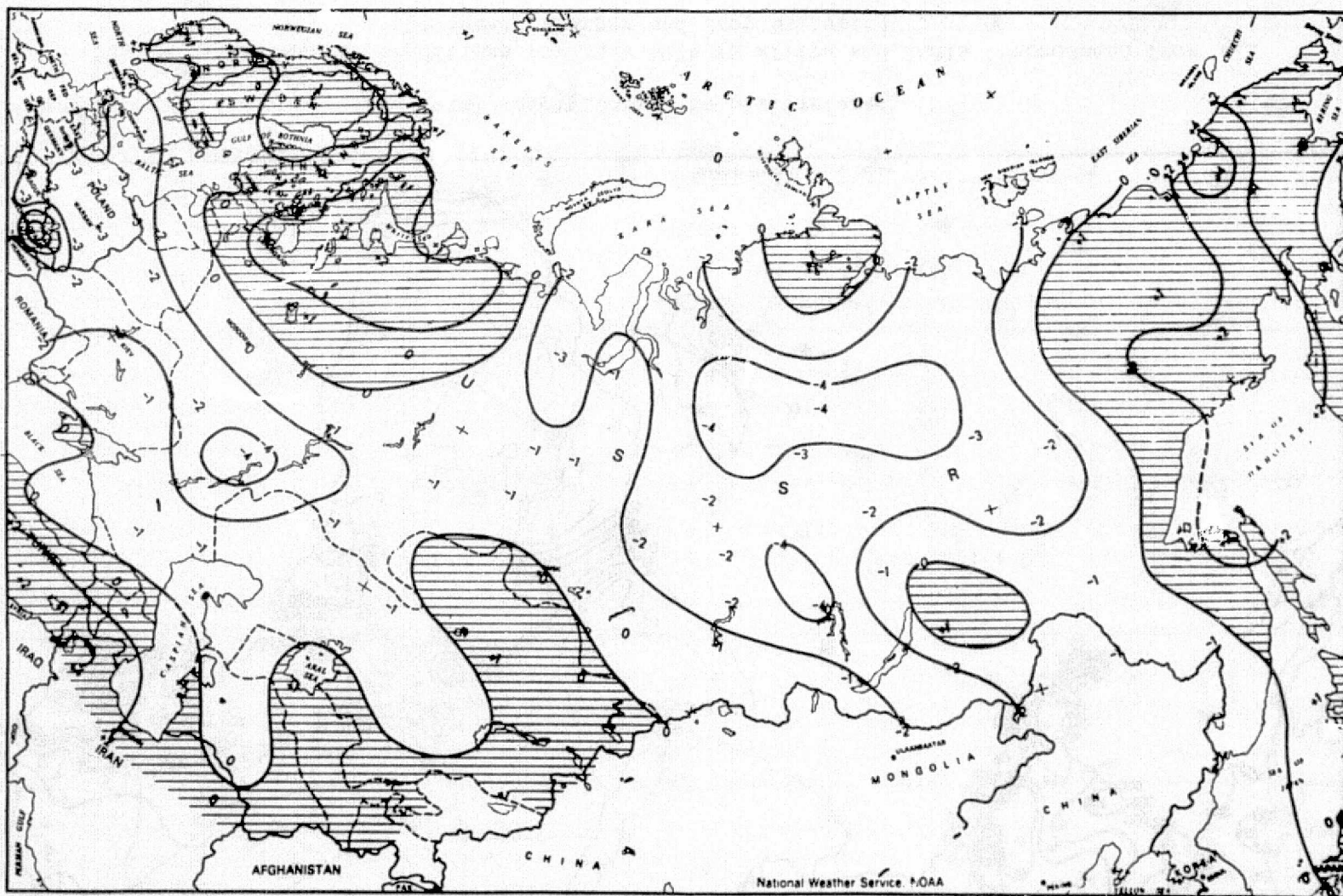
(b) Percentage of normal precipitation. Shaded areas are 100 percent or more.
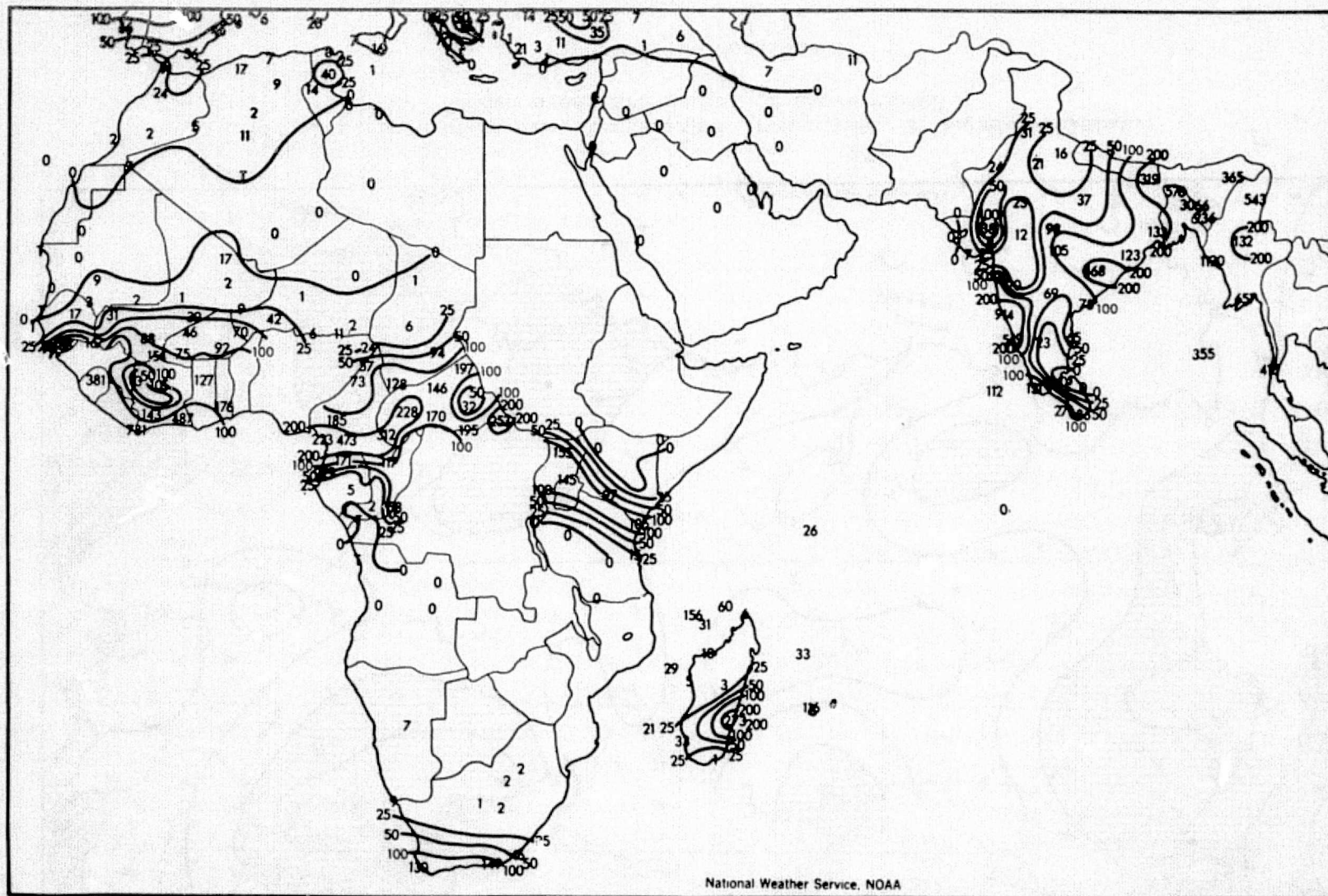
Figure 3-1.- Continued.

(c) Average temperature in degrees Celsius.

Figure 3-1.- Continued.

(d) Departure of average temperature from normal in degrees Celsius.
Shaded areas are normal or above normal.

Figure 3-1.- Concluded.

(a) Total precipitation in millimeters.

Figure 3-2.- Weather conditions for June 1974 in Africa and India (reproduced from the Weekly Weather and Crop Bulletin).

(b) Percentage of normal precipitation. Shaded areas are 100 percent or more.

Figure 3-2.— Continued.

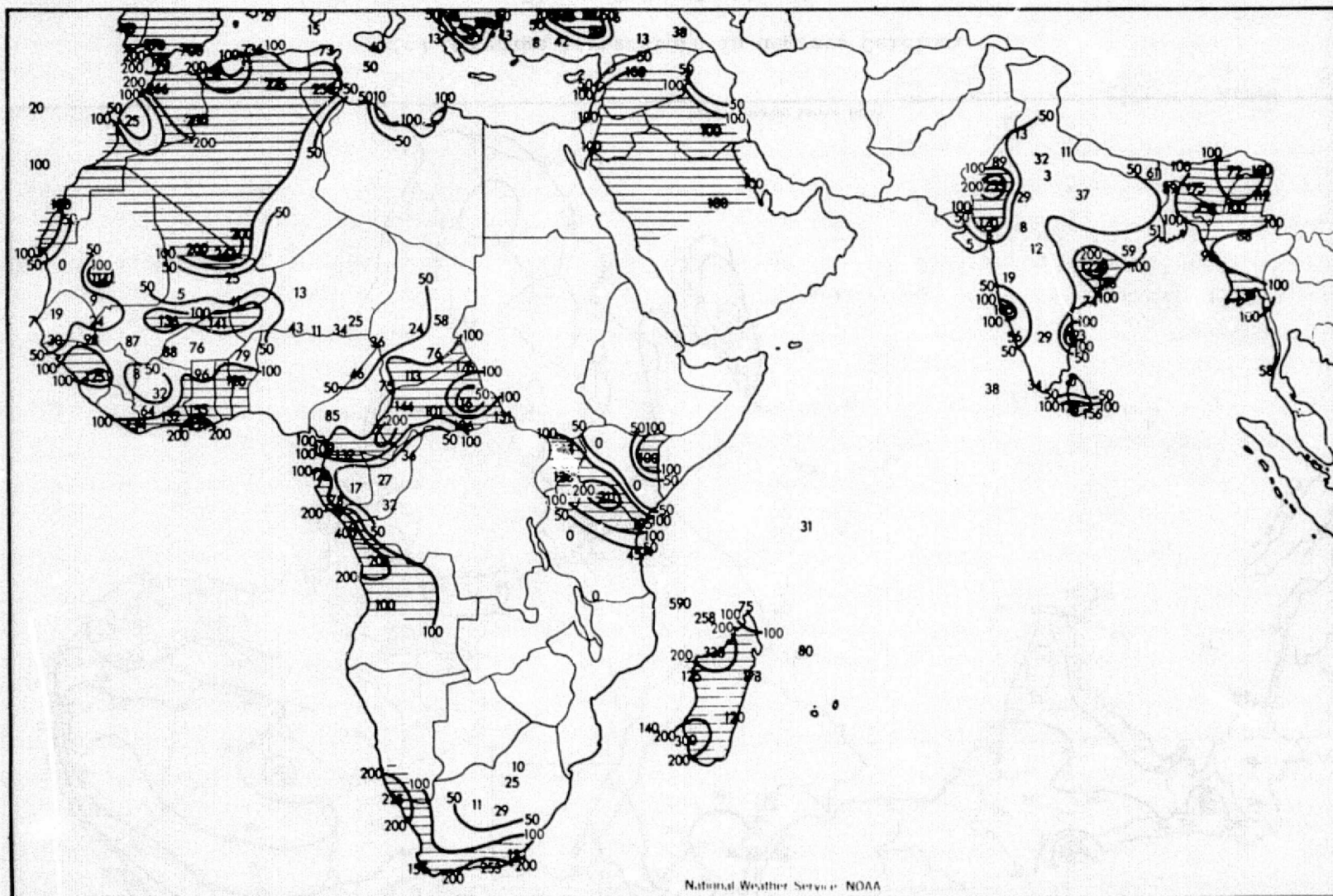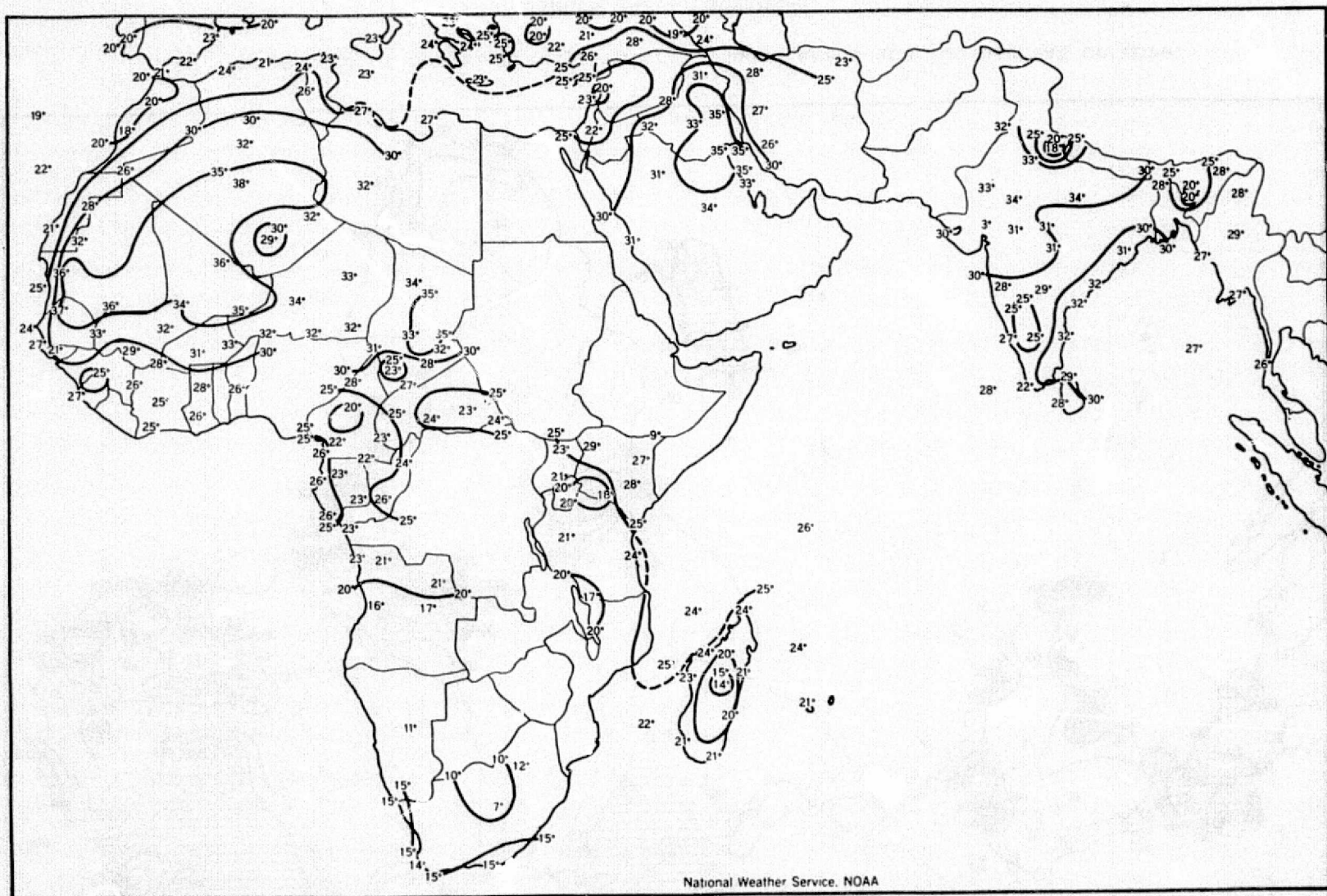(c) Average temperature in degrees Celsius.

Figure 3-2.- Continued.

(d) Departure of average temperature from normal in degrees Celsius.
Shaded areas are normal or above normal.

Figure 3-2.- Concluded.
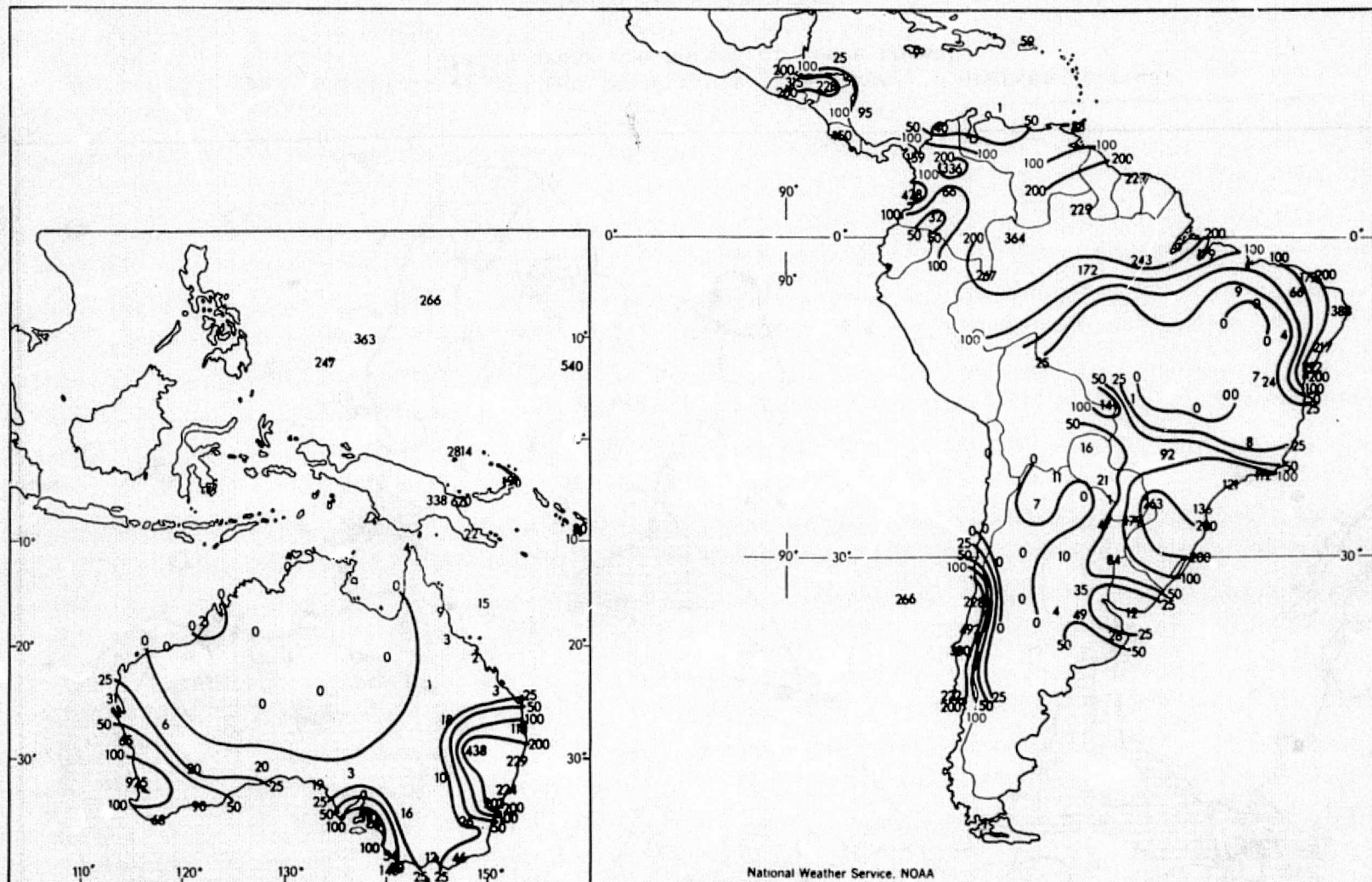
(a) Total precipitation in millimeters.

Figure 3-3.- Weather conditions for June 1974 in South America and Australia
(reproduced from the Weekly Weather and Crop Bulletin).
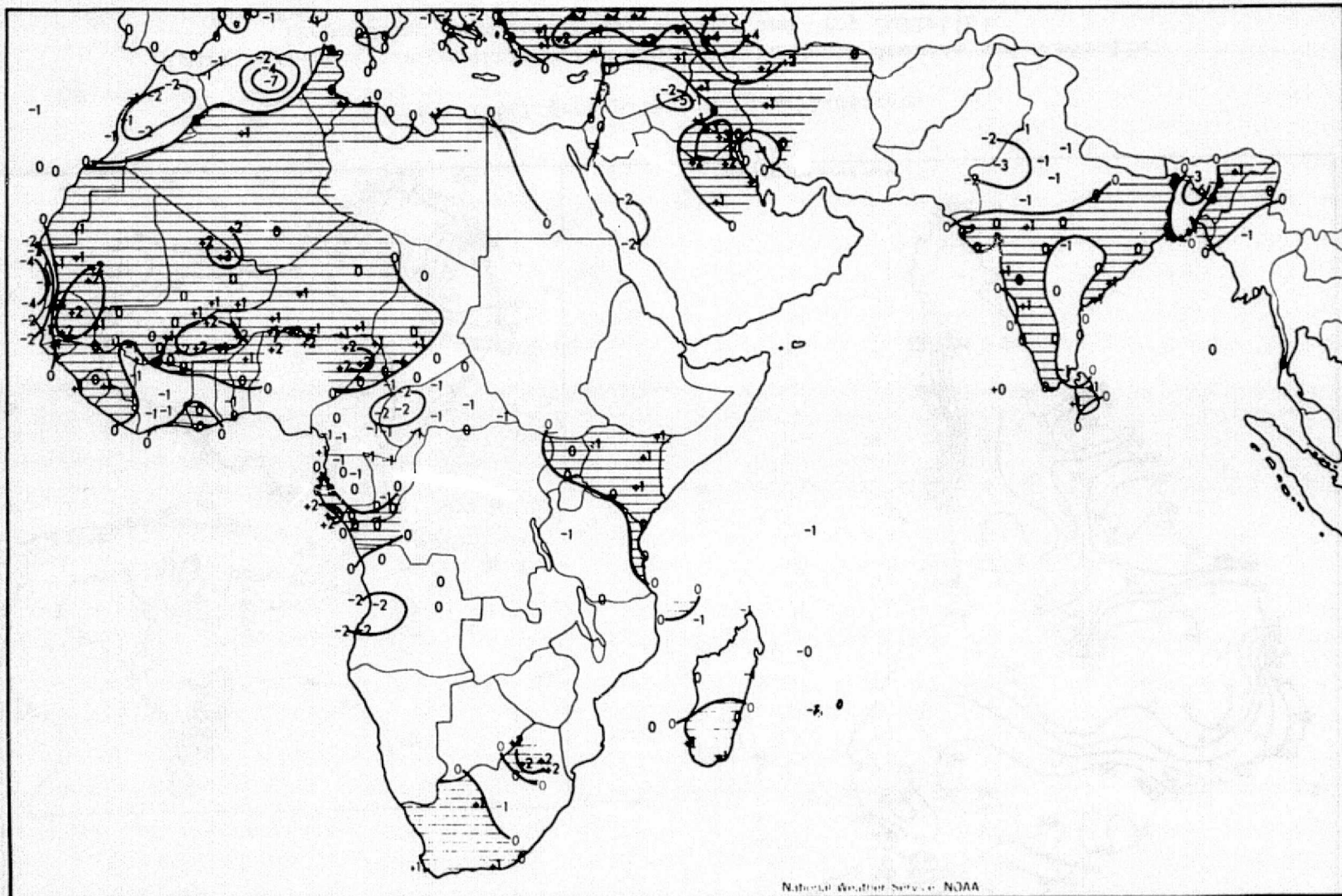
National Weather Service, NOAA

(b) Percentage of normal precipitation. Shaded areas are 100 percent or more.

Figure 3-3.- Continued.

(c) Average temperature in degrees Celsius.

Figure 3-3.- Continued.

National Weather Service, NOAA

(d) Departure of average temperature from normal in degrees Celsius.
Shaded areas are normal or above normal.

Figure 3-3.- Concluded.
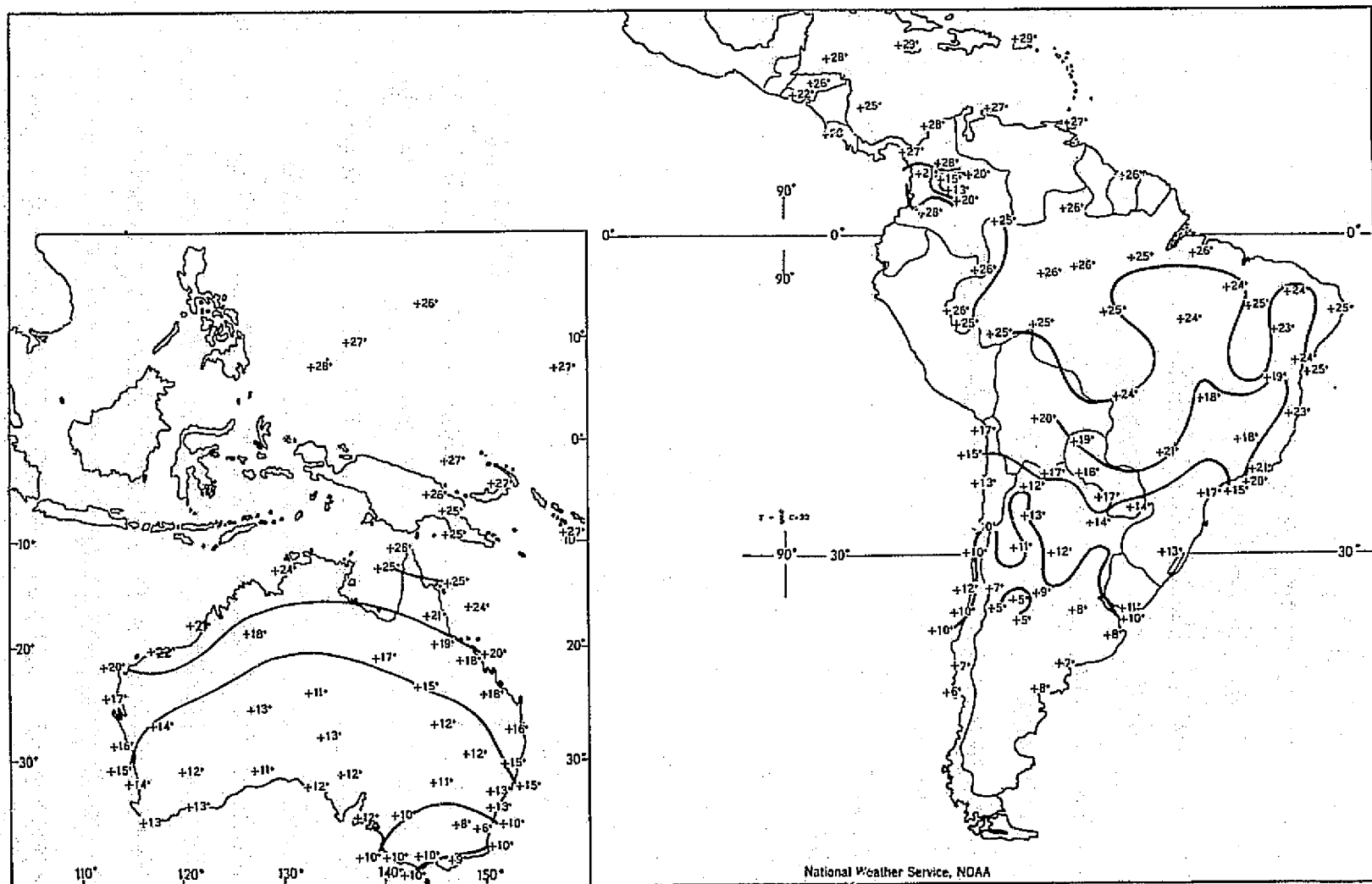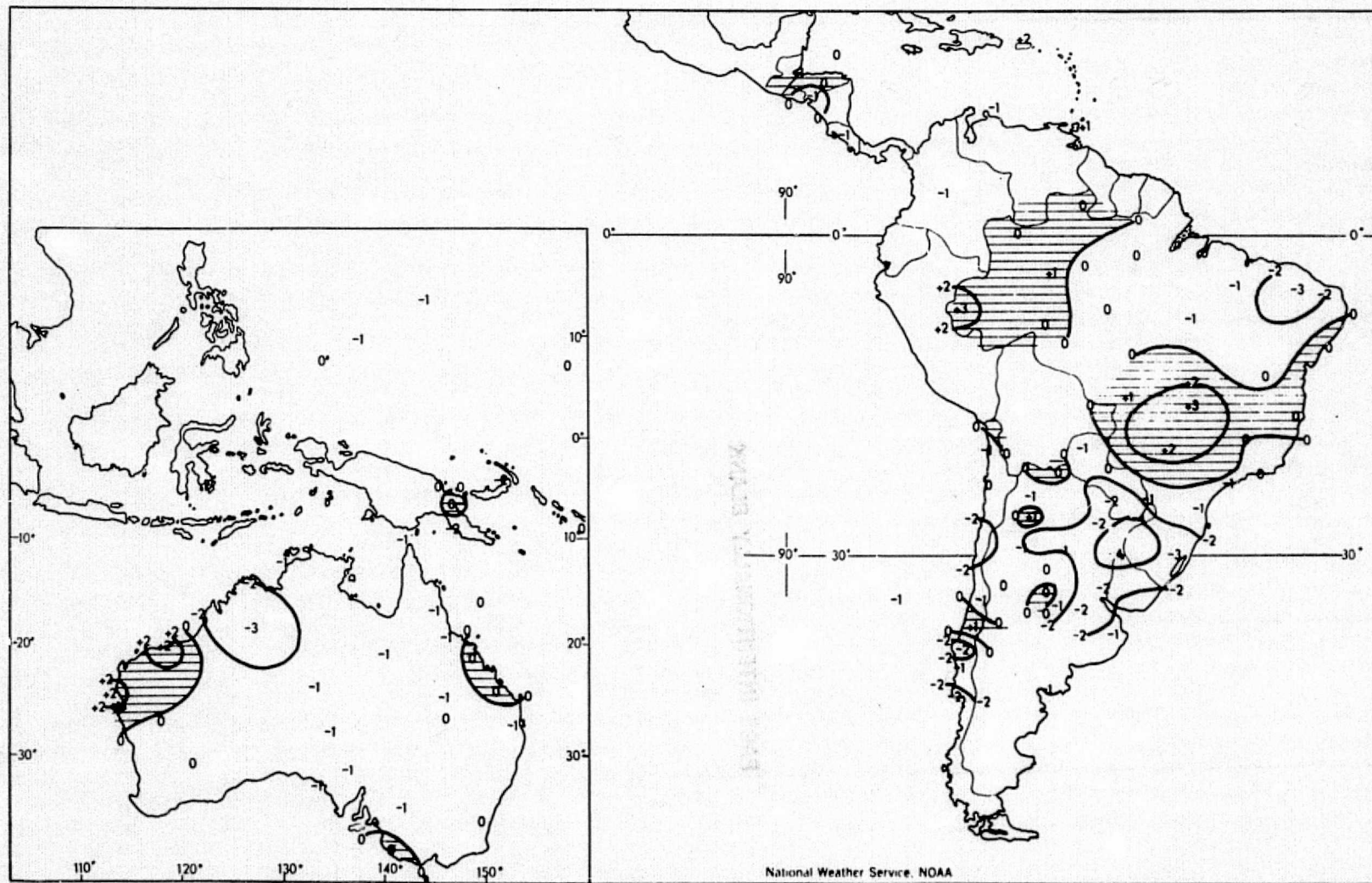
4. APPLICATION OF CROP AND WEATHER STATISTICS IN REAL-TIME DECISIONMAKING

James E. Newman*

Two organizations associated with Purdue University are very much involved in crop modeling and research. The first organization is the Laboratory for Application of Remote Sensing (LARS), which is sponsored by NASA. The second organization is the MIRACLE group; MIRACLE is a code name for a computer crop modeling group. Three PDP-11 units are hooked together, which allows great flexibility in real-time analysis. Data are stored, analyzed, and printed almost simultaneously. The MIRACLE group has been performing a type of detailed modeling that is presently occurring in agricultural sciences. Two very definite approaches presently are being applied to crop modeling in the United States. The first approach, deterministic modeling, is being attempted by most agricultural groups. However, very few groups are using the second approach, stochastic modeling.

The deterministic approach essentially builds a model by taking many experimental data and formulating a mathematical expression from them. The approach involves fitting a curve or line to data for the plant or animal response and then formulating it into a computer program. Some deterministic models are very complex, having several hundred computer-programing steps. Beginning in 1967, detailed climatological data were collected on the alfalfa crop. At the same time, crop growth responses were obtained. After the collection of these data, an alfalfa production model was built. This model was successful in predicting the forage regrowth in a specific plot or a specific field. The success of this technique depends on approximating known environmental responses to the real-time measurements of climatic parameters.

Contained within the first publication on the alfalfa model is a flow diagram of the entire model concerning leaf area, carbon dioxide uptake, and weather-data input (fig. 1 in ref. 4-1). Immediately, various aspects of curve fitting are visible by means of X-Y diagrams. These curves are formulated into the computer program; then, each major plant response is addressed. By adding all plant responses, a model statement can be acquired, and enough details can be discovered to predict what is occurring. If enough detailed data about phenomena exist, the response can be fairly well predicted. This model is concerned with the herbage yield, which is measured by weight per unit area. This model is sensitive enough to predict diurnal changes. Hourly net radiation values and other short-term weather information are used in this model. Data were summarized on an hourly basis. An attempt is being made to model actual physiological responses to measure these physical parameters.

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The prediction model shown in figure 25 in reference 4-1 worked very well. In the second cutting, the harvest yield did not quite agree with the model prediction, because of insufficient information on soil moisture in the model (figs. 26 and 27 in ref. 4-1). Otherwise, the model is 80 to 90 percent accurate. To measure soil moisture, the amount of water between the field capacity or gravity and the permanent wilting point must be quantified for the various layers. Water use by the alfalfa has been estimated by making weekly soil moisture measurements. This technique can be used to predict plant stress or soil moisture deficiencies such as those shown in figures 26 and 27 in reference 4-1. Thus, if enough measurements are programed correctly, accurate predictions can be obtained by using the deterministic model.

Because alfalfa has been modeled rather successfully, the next step was to question the alfalfa management technique in real-time decisionmaking (ref. 4-2). The alfalfa model was the first attempt to accomplish this in practice. Hourly data obtained from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service were used in an approach to real-time decisionmaking. Very detailed alfalfa data that were observed by professional agricultural people were used. These data were programed into a computer, and management practices were predicted every morning. Four remote areas throughout Indiana and the checkpoint at Purdue University were used.

The methods perfected in the alfalfa model and the alfalfa management technique give a summary of 5 to 6 years of effort that began with 2 men and branched out to approximately 30 professionals. Each man spent some time each day obtaining real-time information on a statewide basis; they then related this information to farmers and other decisionmakers in the agribusiness area. Thus, the research effort evolved from rather basic research and development to serving the actual user.

Many events other than weather can affect a crop yield around the world. In 1970, an epidemic of southern corn blight occurred in the United States. The Connecticut Agriculture Experiment Station built a plant disease model for the corn blight. This model, which has approximately 310 steps, is probably the most complete plant disease model in the United States. Several members of the Agricultural Experiment Station at Purdue University programed and tested this model in 1971. Much of the test was conducted on a LARS NASA computer. The Purdue modeling group received the weather information from the NOAA system every 3 hours and then ran the model to predict the disease development and epidemic. Many steps were involved to give an output of how many spores were producing daily. These data corroborated rather closely in most areas of Indiana, the Midwest, and other parts of the United States where they were verified against ground-truth data. This project was a cooperative effort of NOAA personnel, the Purdue modeling group, and the NASA LARS group.

Purdue University has not been involved too directly in stochastic modeling. Although Purdue University has a very fine breeding and pathology program in wheat, it has not done any wheat modeling. In the future, corn- and soybean-yield modeling will be undertaken. The stochastic technique used at Iowa State University is the type model that a group wanting to make worldwide decisions will find most adaptable. Much interplay exists between these two

schools of thought that could be used in future models. At least a 5- to 10-year effort will be required to perfect models giving the type detail that many scientists hope to achieve. A learning process, a verification system, an application system, and a feedback mechanism are necessary. The building and testing of predictive models is a learning process from beginning to end.

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QUESTIONS AND ANSWERS

SUITS: I noticed that you had some interesting results, but did you compare them with any inaccuracy of prediction with any stochastic methods that are commonly used?

NEWMAN: We have not published anything. We are in the process of running some stochastic models against some deterministic models.

SMITH: In speaking of stochastic models, you are mainly talking about mechanistic-type models in which you insert processes. The stochasti model does not have to be only a statistical-type regression fit it can be mechanistically oriented, particularly this interplay betv een ideas that you mentioned when you have imperfect data sources such as precipitation. You do not have a daily precipitation, but you have a probability distribution for the precipitation, which you can use to generate input into your deterministic model.

TRACY: You mentioned that the day-to-day predictions were helpful in terms of day-to-day management. I am rather curious as to what those values might be.

NEWMAN: For example, consider the large commercial farm manager. The most logical time sequence for his decisionmaking is a week. In building our model, we ran it on daily or hourly inputs, depending on how fine a mesh we were using. We ran an output each morning to share with our users. Most inquiries were about spraying programs of pest buildup in the alfalfa model. We certainly followed the weekly trend — that is, we had much interest on Monday morning. Anytime we have updated information, we like to give it to our potential users. Thus, if we had the same question the following morning from another group, we could certainly reply to them using the daily updated information. Most management decisions in the fine mesh with which we are experienced would be once or twice weekly at the most. If you want to share products of deterministic-type models such as we are using, certainly a different set of recommendations would be produced each week.

TRACY: From your experience, to what extent can you make updates and have them be of some value in terms of the accuracy of your predictions? We have been constantly trying to perceive the fact that if we give somebody a bad prediction, we may compound the problem rather than make it better.

NEWMAN: Yes, I would like to comment about that problem. You notice that we are using an alfalfa model because we know the most about the alfalfa crop or crop management system. You will make a mistake if your knowledge is incomplete. Our bad predictions were caught very quickly because we were concerned mostly with pest management. We were constantly observing what we were predicting. If our

observations or ground truth did not agree with our predictions, we would immediately become very concerned. An excellent verifying system must be a major concern in any kind of crop modeling management decision information use. Last season we had a problem given to us. We were asked to predict the energy needs to dry the Indiana corn crop. Because we had no previous experience, we devised a verification method. We obtained the crop planting dates in the crop-reporting zones from the U.S. Department of Agriculture Statistical Reporting Service, and we obtained the maturity series from the seed industries. We put growing-degree-day constants on all maturity series, which multiplied out to 243 variables. We stored into the computer the normal growing-degree days for every week until crop maturation in the fall. The moment the corn was in the ground, we ran a forecast using normal weather, which was obviously erroneous. We substituted the real data as fast as it came in every week. The forecast for energy needs changed every time because the real data was different from the normal. By September 10, we knew the progress of the corn crop was such that the energy need would not be 48 million gallons of gas as it had been in 1972. The requirement was predicted to be 39 million gallons. By October 1, the final forecast was 34 million gallons; however, 32 million gallons were used. Thus, a 6-percent error was made. If you update your information with real-time data, it is very applicable to a stochastic-type system.

SAKAMOTO: You mentioned real-time data. We are concerned with predicted information — that is, 2 to 3 days in advance. Realizing the situation at Purdue University concerned with the NOAA weather wire, do you anticipate using predicted information in your models for management practices?

NEWMAN: We have never tried predicted information in management decisions because we feel that our skill in performing real-time analysis has an error term of 10 to 20 percent, depending on what we are doing. The skills with which to foretell future physical weather parameters also have an error term. However, we certainly relay such information in our agricultural weather forecast. We write farm advisories that are based on today, tonight, and tomorrow and on a 5-day outlook. We have never tried predicted information in our modeling technique. The question always arises as to how to sort out the error terms.

NICHOLS: Have you studied the problem of sampling intensity in terms of frequency? For example, if hourly temperature measurements were inserted to run the model, what happens if you look at them four times a day and perform some curve fitting to obtain the intermediate value? How does the model respond to this less frequent sampling?

NEWMAN: We used hourly, 3-hour, 6-hour, and daily sampling. We obtained the best prediction with the 3-hour sampling. That experience is the

only one that I know of in our modeling group for that particular question. I would suspect that in some stochastic-type modeling — particularly when an entire region is sampled such as the hard-spring wheat region in Canada — a much longer time period would be optimal.

BARGER: When we were working with the corn-blight fungus to produce an infection that took 6 to 8 hours in liquid water within favorable temperature range, we were attempting to measure the rate of development; therefore, we needed a fairly frequent and short-time-interval observation on the moisture and temperature conditions.

PITTS: I realize this program is experimental, but I was wondering if you are keeping track of cost as compared to benefits in your program?

NEWMAN: No one has ever asked us for that information.

PITTS: Could you give a detailed account of your pest management activities? What exact management practices were conducted on the basis of your forecasts, and what was the response time of the individual farmer to these different practices?

NEWMAN: In these counties in which we operated, instead of having a shotgun-type spray program for pest control, we were able to limit the amount of spraying to approximately 50 percent. I do not know if that limit will hold every year. This reduction occurred in very well defined situations in which we hit the pest in the right stage for the minimum treatment. We limited the amount of spraying because of the emphasis on the overuse of pesticides in the environment.

5. WHEAT-GROWTH/ENVIRONMENT/YIELD RELATIONSHIPS

By J. R. Haun*

Basically, the three parts of the program are as follows: identification and quantification of plant growth changes, statistical analysis, and testing of resulting models. Statements of two persons provided significant background for plant observation. Prof. Newman (ref. 5-1) emphasized the need for more attention to measurements or observations of plant responses to environmental factors — that is, the dependent variable in bioclimatic studies needed improvement. Harry Clements, who used multiple-regression techniques and plant observations on sugarcane, was of the opinion that there is no precise way to measure the rate or vigor of plant growth. "Chemical analysis seemingly cannot always distinguish between stunted and vigorously growing plants (Ferwerda, 94) any more perhaps than a peddler's nag can be distinguished biochemically from a fine steed. It would seem that the physiologist who wishes to determine the vigor of a crop must do so ignominiously by counting leaves to determine their rate of emergence . . . ." (ref. 5-2). This method is indeed a good tool to evaluate crop responses.

Millions of dollars have been spent on controlled-environment rooms; however, no one has a model developed in a controlled environment that can be applied in the field because environmental factors are highly interrelated. Thus, plants respond to these very nebulous interactions in ways that defy analysis by typical procedures in a controlled environment. The high-speed computer and new statistical techniques provide for analysis of many more interactions than could ever be simulated in a controlled environment. However, before analysis can be accomplished, a very sensitive and very accurate measurement of plant development is needed. In traditional sampling methods, such as periodic harvest and determination of dry weight, the sampled plants are destroyed. This method initiates sampling difficulties, a need for additional replication, and other statistical problems. If physical measurements are used, such as a ruler for leaf area, inevitable curvilinear relationships are involved. Essentially, all biological responses are curvilinear in some way.

The U.S. Department of Agriculture, interested in development of new crops, worked on tephrosia, kenaf, crambe, and other potentially valuable chemurgic crops. In publishing this work in 1964 (ref. 5-3), a study of corn was included to illustrate the overall procedure used on existing or established species. A plant with four leaves visible and development of the fifth leaf quantified in numerical form is shown in figure 5-1. From a physiological or botanical standpoint, this system may seem ridiculous because the fifth leaf at

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stage 4.0 had been developing for some time before it came into view. Likewise, when the leaf is "completed" at the 5.0 stage, it will grow even more. This midportion of the development of an organ (leaf) is roughly linear. This fact will be evident in later illustrations and discussions.

A drawing of the garden pea by Higgins is depicted in figure 5-2. Because of the morphological diversity during development, the garden pea was an excellent plant for quantification of growth and development. Consequently, this plant was used as an integrator of environmental conditions to schedule plantings of vegetable crops. The garden pea was a better indicator than degree-day or degree-hour summations because it reflected the total influence of weather on crop development.

The possibility of using this procedure with a perennial-type or woody plant was questioned. With stored nutrients and previous growing conditions complicating the problem, the responsiveness of leaves or growing points to daily environmental variations would be uncertain. A view of the quantified development of a peach leaf is shown in figure 5-3. From subsequent analysis of daily observations of leaf development and environmental variables, procedures applied to annual crops were found to be applicable to woody plants. However, in the case of the peach, something better was available for quantification of growth rate. The daily expansion of diameter of the peach fruit was measured and was found to be more closely related to what is important to predict — namely, yield.

Another illustration of quantification of plant development is the banana (fig. 5-4). The novelty of this plant is that it is large enough that an investigator can drive by to take a reading on the stage of development. Enough pictures of stages for this illustration were difficult to find because the photographs were made only during a 2-day period. Time-lapse photography would have been more satisfactory.

The stages used in quantification of wheat development are presented in figure 5-5. The emerging leaf is considered the reference leaf, and its stage is determined by comparison with the next oldest leaf. The stage of development is distinguished by relative length, not absolute length. A wheat culm has a definite number of leaves. When the last leaf is completely visible, the elongation of the culm below the flag is quantified, and the stage is considered complete when the boot is just beginning to swell. These stages are arbitrary designations that were verified by later tests to determine the suitability of spacing. The principle of quantitative morphology as compared to physical measurement is illustrated in figure 5-5 (fourth stage). The leaf on the center plant is larger than the two more advanced stages on the right. Obviously, the stage of plant development of the center plant is less than those stages on the right because the head is at an earlier stage of emergence.

A diagrammatic view of two hypothetical plants is depicted in figure 5-6 to emphasize quantification of morphological change as compared to physical measurements. The plant on the left is drawn exactly half as large as the one on the right; however, the morphological index would be 2.5 for each of the plants because both have 2.5 leaves. Soil fertility and other factors also

influence wheat yield. Interactions between fertility and various environmental factors also exist. For modeling purposes, fertility is assumed to be of an average or static nature throughout a field or among fields in a state. The important factors are the influence of temperature, solar radiation, and moisture on the average plant. The use of quantitative morphology provides a common denominator for the development of large and small plants. The logic of this statement is based on the fact that fluctuations of daily growth rate are more important than total size.

Pope (ref. 5-4) took height measurements of the tip of each barley leaf as it developed (fig. 5-7). During most of the season, he simultaneously measured two leaves. As expected, the upper end of the development curve for each leaf indicated a reduction in growth rate — that is, as the leaf reached its final size, it grew slower and slower. In the system of quantitative morphological stages that have been described, the series of observations on each leaf begins when it is first visible and ends when the next leaf is visible. The shaded areas correspond in time with measurements made by Pope and those made by the quantitative morphological system (fig. 5-7). The portions of these growth curves common to both methods are approximately linear.

An example of data obtained from daily observations of wheat is shown in table 5-I. Plants to be observed are labeled in such a way that they may be easily found on successive days. The indicated growth rates of 0.12, 0.08, and 0.22 give some indication of the fluctuations that may be expected. The average crop observer would see essentially no difference in these plants from day to day. Also, to find statistical significance from dry-weight determinations for differences in growth rates among days would be difficult because the youngest leaves are so small that growth would not be reflected in accurate weight differences. Several ways exist to determine whether the observations are rational and objective. Results of an analysis of variance of average wheat development are shown in table 5-II. In this analysis, 325 individual plant growth-rate determinations were tested to compare day-to-day differences (presumed to result from weather variations) with differences in amount of development associated with each 0.1 unit. A highly significant mean square for days and a relatively insignificant value for tenths indicate that the observations are objective and that they represent approximately equal increments in plant development. Any differences in growth-rate values resulting from inaccuracies in the method are relatively insignificant when compared with the differences caused by weather — that is, among days.

A graphical presentation of cumulative growth data typically found in the literature is illustrated in figure 5-8. A similar presentation of cumulative data for winter wheat is depicted in figure 5-9. The nearly horizontal portions during January and early February are due to unfavorably cold conditions. Cumulative data of this type are not used in the analyses. The small daily variations in slope (figs. 5-8 and 5-9) caused by changes in growth rate are used as the dependent variable.

In contrast to the cumulative graph, growth-rate graphs for winter wheat are presented in figures 5-10 and 5-11. The day-to-day variations in growth

rate of these plantings are clearly visible. Fluctuations in estimated soil moisture and minimum and maximum air temperature are contrasted to growth rate.

Basic environmental variables generally used in the studies were maximum and minimum air temperature, maximum and minimum soil temperature, solar radiation, evaporation, and estimated soil moisture. In addition, various transformations and lagged variables were used. Transformations included the square, cube, sine, selected cross products, and 7-day running-average mean air temperature. Consideration of lag time was suggested by simple two-factor correlations of growth rate with individual environmental factors (tables 5-III and 5-IV) — that is, the value -0.164 in table 5-III is the correlation coefficient r between the growth rate of this planting and minimum air temperature on the same day as the observation; the value -0.220 is the r between the growth rate and the air temperature of the previous day. Although the trends of change in r values suggest important relationships, their associated linear regression coefficients cannot be used directly in growth models. Because of the highly intercorrelated nature of environmental factors, only a multiple-regression procedure would be rational for an analysis of field data under uncontrolled environmental conditions.

In table 5-III, the r values for minimum air temperature were negative at all lag times, which suggests that wheat grows better even below freezing than it does at some normal level. An explanation for this situation was found in the curvilinear distribution of growth-rate values throughout the season. Early in the season, values were relatively high and increased with time, whereas late in the season, values were relatively low and decreased with time. Results of analyses performed during two parts of the season are shown in table 5-IV. Growth was positively correlated with soil temperature in the first part of the season, negatively correlated in the second part of the season, and negatively correlated when the entire season was considered. Thus, in the early part of the season, the soil temperature was more favorable for wheat growth. These simple two-factor correlations emphasize that consideration of lag time in the effect of variables is important and that the lag time may change during the season. Any model that is designed to involve cause-and-effect relationships should definitely include these considerations.

The terminal step in a stepdown multiple-regression analysis procedure on winter wheat data is presented in table 5-V. The three independent variables remained; however, other basic and transformed variables were excluded because of their insignificance in earlier steps. A relatively high coefficient of determination R^2 at 0.883 is apparent, and highly significant Student's t values are apparent for the following independent variables: product of minimum air temperature and maximum air temperature squared, product of percent estimated soil moisture squared and maximum air temperature, and 7-day running-average mean air temperature cubed. The prediction equation from table 5-V for 1971-72 data applies to 1966 data presented in figure 5-12. The solid line is the actual growth rate; the broken line is the growth rate calculated by using coefficients from table 5-V. A simplified view of the same data expressed as a 3-day running average is depicted in figure 5-13.

One of the best analyses on spring wheat is illustrated in table 5-VI. These statistics show the value of solar radiation and the factors of plant development (age and cumulative growth). Because the main interest was in developing a model for currently published weather data, the variables were limited to air temperature, precipitation, and estimated soil moisture. The results of an analysis of the first part of the season are shown in table 5-VII. Lag times were important to consider; moreover, lag times shifted from the first part of the season to the second part of the season. Separate models were prepared for the two different parts of the season. The analysis of June data (used to represent the first part of the season rather than the exact calendar days of June) is presented (table 5-VII) with the following three variables: maximum air temperature lag 1 squared, minimum air temperature squared, and estimated soil moisture lag 4. People continually use R^2 to indicate the quality of a regression; R^2 should never be mentioned without including the number of degrees of freedom. In this example, R^2 would automatically be 1.00 if 21 variables existed. Basically, three elements are used as criteria for preliminary evaluation of a multiple-regression analysis: the R^2 (relative to degrees of freedom), reduction in standard error of the dependent variable, and Student's t values — that is, significance of the variables involved. However, the most important criterion is how well the prediction equation will work on data not related to the analysis from which it was derived. Statistics of the analysis for the second part of the season based on the July data are shown in table 5-VIII. This analysis provides a slightly better R^2 and a slightly better group of partial regression coefficients for the following variables: maximum air temperature lag 6, air temperature spread lag 7, and estimated soil moisture squared.

The manner in which the prediction equations from these two analyses are used in a yield prediction model for spring wheat is shown in figure 5-14. The first equation for calculating estimated soil moisture is based on the Thornthwaite-Mather system. The model was found to work on 10-day temperature averages, which were used to make the data easier to handle. The model is actually based on daily growth and environmental data. Earlier, a model on 10-day average growth values was constructed, but it did not work very well. Daily values of growth rate are assumed to reflect differences in weather from day to day. Thus, when the 10-day average growth rate is used as the dependent variable, growth and environment relationships are obscured because the extremes of growth response and the extremes of environmental variables are not used. Considering the importance of curvilinear relationships, a model based on 10-day average growth rates would be less accurate than one based on daily values. The fourth equation of the model introduces the effect of preseason moisture, which is very important in spring wheat production. Seven years of yield data for the counties of North Dakota were used in the regression to establish these coefficients. Statistics of this regression are depicted in table 5-IX. The final equation was added when the logarithm of the yield was found to fit somewhat better than the untransformed yield. Therefore, a predicted yield is produced by the antilogarithm of the result of the previous equation.

Predicted average state yields that were obtained for North Dakota are shown in figure 5-15. Years having circles were involved in formulation of the preseason moisture and do not represent a conclusive test of this system. Predicted yields for three provinces in Canada are illustrated in figure 5-16. The relationship of predicted yields to actual yields is not statistically significant because not enough range exists in the data.

The prediction model was applied to the New Lands area of the U.S.S.R. for the period from 1962 to 1970 (ref. 5-5) (fig. 5-17). Identical values of figure 5-17 are shown in figure 5-18 averaged by districts and years and adjusted by the regression equation from figure 5-17. This type relationship was obtained by applying this model to data totally unrelated to the data on which the model was constructed.

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ROBERTSON: You are using the term growth, when, actually, I think you are talking about the maturational rate of crop development, not growth in terms of accumulation of dry matter. I think we should get this matter straight because a very great difference exists between growth and development.

HAUN: Our system for quantification of changes in plant morphology involves both growth and development. The procedure relates to development when new leaves and other distinctly different parts appear; it relates to growth (in the sense of cell division and expansion) when individual plant parts increase in size. As you have suggested, our index is also an indication of the maturational rate of development.

ROBERTSON: In terms of spring wheat, I do not think any relationship exists between the development rate and yield. I have worked with spring wheat all over Canada and have found no relationship. You can get wheat that will develop very rapidly and yield very well if the conditions are right. However, you can get wheat that will develop very rapidly and yield very poorly if the conditions are more favorable for development than growth. For spring wheat, the two processes are unrelated, and varieties respond differently to the same climatic factors. Are you studying winter wheat?

HAUN: We have studied both winter and spring wheat. The relationship between development rate and yield over a critical period of the season was established for spring wheat by the regression (table 5-IX) from which coefficients for the growth index were obtained in figure 5-14. If the statistical significance of these coefficients had not been adequate to indicate the relationship between growth rate and yield, to include them would be impossible. A further test of the model was obtained in the application to U.S.S.R. weather data.

ROBERTSON: You made the comment that daily photoperiod was not important. Was that for spring or winter wheat? If you had been using spring wheat over a very large range of day lengths, I think you would have found that the photoperiod would have been a very important factor in the development rate. A weakness of regression is that if any one variable does not have very much variation, then the influence of that variable on some growth or development factor will show up as being rather weak. Many variables never show up with strong partial regression coefficients.

HAUN: We have used day length in some of our analyses on both types of wheat and have found it to be a significant factor. However, for the reasons you have stated and for a more important reason, this variable has not been included in the final model — namely, a

variable with a more-or-less constant rate of change frequently results in what we have termed a long-term trend effect. For example, if the normal trend of change in growth rate for a particular crop increases steadily at a time when day length also increases steadily, then a highly significant correlation will result. The resultant prediction equation will be unbalanced in favor of this tautological relationship, which will not contribute to the accuracy of growth and/or yield predictions that are based on daily weather differences.

HARTLEY: I have one question concerning the use of the leaf count in the morphological observation. Will the spacing of plants have an effect on the morphological stage?

HAUN: Within ranges used commercially, possibly some effect would be present; however, we have to assume a static or average value for an area. Some plants will be short; some will be tall. Some plants will have been heavily fertilized; some will have been lightly fertilized. All these factors will influence yield. However, the environment is the major factor influencing variability of county, state, or district yields from year to year. Quantitative morphological observations provide sensitive indicators of weather effects. From this information, models can be developed for predicting growth rates. We then have to incorporate the influence of preseason moisture. Eventually, for longer periods of prediction, the influence of changing technology will need to be incorporated.

TABLE 5-I.- EXAMPLE OF WHEAT OBSERVATION DATA

Plant no.	June 5	June 7	June 8	June 9
Values				
1	3.3	3.6	3.7	4.0
2	3.5	3.7	3.7	4.0
3	3.3	3.6	3.6	3.7
4	3.2	3.5	3.6	3.7
5	3.5	3.7	3.8	4.1
6	3.4	3.6	3.7	4.0
7	3.0	3.2	3.2	3.3
8	3.5	3.7	3.8	4.1
9	3.4	3.7	3.8	4.1
10	3.2	3.4	3.6	3.7
Average value				
--	3.33	3.57	3.65	3.87
Change				
---	--	0.24	0.08	0.22
Growth rate				
---	--	0.12	0.08	0.22

TABLE 5-II.- ANALYSIS OF VARIANCE OF AVERAGE WHEAT DEVELOPMENT[a]

Source of variation	Degrees of freedom (df)	Mean square (MS)
Observation, days	36	[b]3.765
Average development associated with each 0.1 unit of observation	9	.783
Error	324	1.360

[a]Associated with each 0.1 unit for 37 observations of 10 wheat plants during the period from May 29 to July 16, 1966, Dickinson, North Dakota.

[b]Significant at the 0.1 level of probability.

TABLE 5-III.- CORRELATION COEFFICIENTS BETWEEN WHEAT GROWTH RATE AND ENVIRONMENTAL FACTORS ON

THE DAY OF GROWTH OBSERVATION AND THE FIVE PREVIOUS DAYS[a]

[df = 60]

Environmental factor	Day					
	0	1	2	3	4	5
Minimum air temperature	-0.164	-0.220	[b]-0.299	[c]-0.382	[c]-0.434	[cd]-0.506
Hours above 50° F	[cd]-.361	[b]-.292	-.159	-.137	-.135	-.150
Minimum soil temperature	[c]-.405	[c]-.454	[c]-.521	[c]-.569	[c]-.604	[cd]-.641
Solar radiation	.061	.200	[bd].303	[b].284	.229	.167
Maximum relative humidity	-.145	[b]-.256	[b]-.291	[bd]-.311	[b]-.282	[b]-.256
Soil moisture at a 12-in. depth	[cd].454	[c].429	[c].420	[c].408	[c].382	[c].358
Day length	[cd].698	[c].683	[c].662	[c].638	[c].608	[c].572

[a]Planting number 1 at Dickinson, North Dakota.

[b]Indicates significance at the 5-percent level of probability.

[c]Indicates significance at the 1-percent level of probability.

[d]Maximum lag-time effects.

TABLE 5-IV.- LAG-TIME COMPARISONS AND PEAK CORRELATION COEFFICIENTS

FOR WHEAT GROWTH RATE WITH MINIMUM SOIL TEMPERATURE[a]

Plant no.	First part of season		Second part of season		Entire season	
	Lag time (b)	r	Lag time (b)	r	Lag time (b)	r
1	0	[c]0.527	0	-0.211	7	[c]-0.658
2	0	[c].586	2	-.329	4	[c]-.597
3	0	[c].660	4	[d]-.503	4	[c]-.543
4	0	[c].636	5	[c]-.703	4	[c]-.470
5	0	[c].701	5	[c]-.662	5	[c]-.443

[a]Dickinson, North Dakota.

[b]Number of days lag time in peak effect.

[c]Indicates significance at the 1-percent level of probability.

[d]Indicates significance at the 5-percent level of probability.

TABLE 5-V.– ANALYSES FOR THE DEPENDENT VARIABLE

GROWTH RATE OF WINTER WHEAT[ab]

(a) Variance table

Source	df	MS	F	Probability > F	R^2
Regression	3	0.14905	329.3	0.0001	0.883
Error	131	.00045	—	—	—
Corrected total	134	—	—	—	—

(b) Regression coefficients and statistics of fit

Parameter	Partial regression coefficients	Student's t for HO:B = 0	Probability >|t|
Intercept	-5.7764×10^{-3}	—	—
Independent variables[c]			
Product of minimum air temperature lag 0 and maximum air temperature lag 1 squared	1.0663×10^{-5}	10.38	0.0001
Product of estimated soil moisture lag 0 squared and maximum air temperature lag 1	4.0365×10^{-7}	9.56	.0001
Seven-day running-average mean air temperature cubed	7.3388×10^{-6}	4.88	.0001

[a]Clemson, South Carolina, 1971–72.

[b]From World Meteorological Organization (WMO) Symposium on Agro-meteorology of the Wheat Crop, Braunschweig, Germany, 1973.

[c]All temperatures in degrees Celsius.

5-13

TABLE 5-VI.- ANALYSES FOR THE DEPENDENT VARIABLE GROWTH RATE OF CRIM WHEAT[a][b]

(a) Variance table

Source	df	MS	F	Probability > F	R^2
Regression	13	0.14150	42.0	0.001	0.733
Error	199	.00337	---	—	---
Corrected total	212	—	---	---	---

(b) Regression coefficients and statistics of fit

Parameter (c)	Partial regression coefficients	Student's t for HO:B = 0	Probability >|t|
Intercept	4.7279×10^{-1}	4.62	0.0001
Age cubed[d]	1.69×10^{-6}	6.05	.0001
Cumulative growth	-9.5819×10^{-2}	4.22	.0001
Cumulative growth squared	1.1878×10^{-2}	3.47	.0010
Cumulative growth cubed	-8.4837×10^{-4}	4.81	.0001
Maximum soil temperature squared lag 1	1.7166×10^{-2}	4.92	.0001
Maximum soil temperature lag 4	-3.9855×10^{-2}	4.06	.0002
Maximum soil temperature lag 4 squared	1.1347×10^{-3}	4.64	.0001
Product of age and minimum soil temperature lag 4	-1.5138×10^{-3}	7.01	.0001
Product of cumulative growth and minimum soil temperature lag 4	6.9203×10^{-3}	5.68	.0001
Product of cumulative growth and percent estimated soil moisture lag 2	5.1747×10^{-4}	3.60	.0007
Product of minimum air temperature and maximum air temperature lag 1	-4.7436×10^{-4}	4.33	.0001
Product of solar radiation lag 1 and minimum air temperature	3.030×10^{-5}	4.94	.0001
Product of solar radiation lag 1 and percent estimated soil moisture lag 2	-5.16×10^{-6}	3.16	.0022

[a]Dickinson, North Dakota, 1967.

[b]Reference 5-6.

[c]All temperatures in degrees Celsius.

[d]Age in days from emergence.

TABLE 5-VII.— MULTIPLE REGRESSION RESULTS FOR GROWTH RATE OF WHEAT[a]

(a) Dependent variable

Variable	Value
Coefficient of determination	0.63800
Regression constant	-.06495
Degrees of freedom	22
Standard error of dependent variable	
Original	.07300
Final	.04700

(b) Independent variable

Variable	Coefficient	Student's t
Maximum air temperature[b] lag 1 squared	0.0000170	1.690
Minimum air temperature[b] squared	.0000385	[c]2.188
Estimated soil moisture[d] lag 4	.0443400	1.497

[a]Dickinson, North Dakota, June 1966, combined plantings.

[b]All temperatures in degrees Fahrenheit.

[c]Significant at the 0.05 level of probability.

[d]Inches of moisture available in upper 2 feet.

TABLE 5-VIII.- MULTIPLE REGRESSION RESULTS FOR

GROWTH RATE OF WHEAT[a]

(a)   Dependent variable

Variable	Value
Coefficient of determination	0.77800
Regression constant	.30071
Degrees of freedom	22
Standard error of dependent variable	
Original	.09100
Final	.04600

(b)   Independent variable

Variable	Coefficient	Student's t
Maximum air temperature[b] lag 6	-0.00283	2.025
Air temperature[b] spread lag 7	-.00191	1.447
Estimated soil moisture[c] squared	.02633	[d]4.799

[a]Dickinson, North Dakota, July 1966, combined plantings.

[b]All temperatures in degrees Fahrenheit.

[c]Inches of moisture available in upper 2 feet.

[d]Significant at the 0.01 level of probability.

TABLE 5-IX.- REGRESSION COEFFICIENTS AND STATISTICS OF FIT FOR THE DEPENDENT VARIABLE OF WHEAT YIELD[a]

$$[R^2 = 0.589; \ df = 331]$$

Source	Partial regression coefficients	Student's t for HO:B = 0	Probability $>|t|$
Intercept	-0.87249	---	---
Independent variables			
Growth index	2.42169	11.81	0.0001
Growth index squared	-.37967	7.33	.0001
Preseason precipitation[b]	.35686	11.02	.0001
Preseason precipitation squared	-.00841	4.37	.0010
Product of growth index and preseason precipitation	-.09218	7.02	.0001

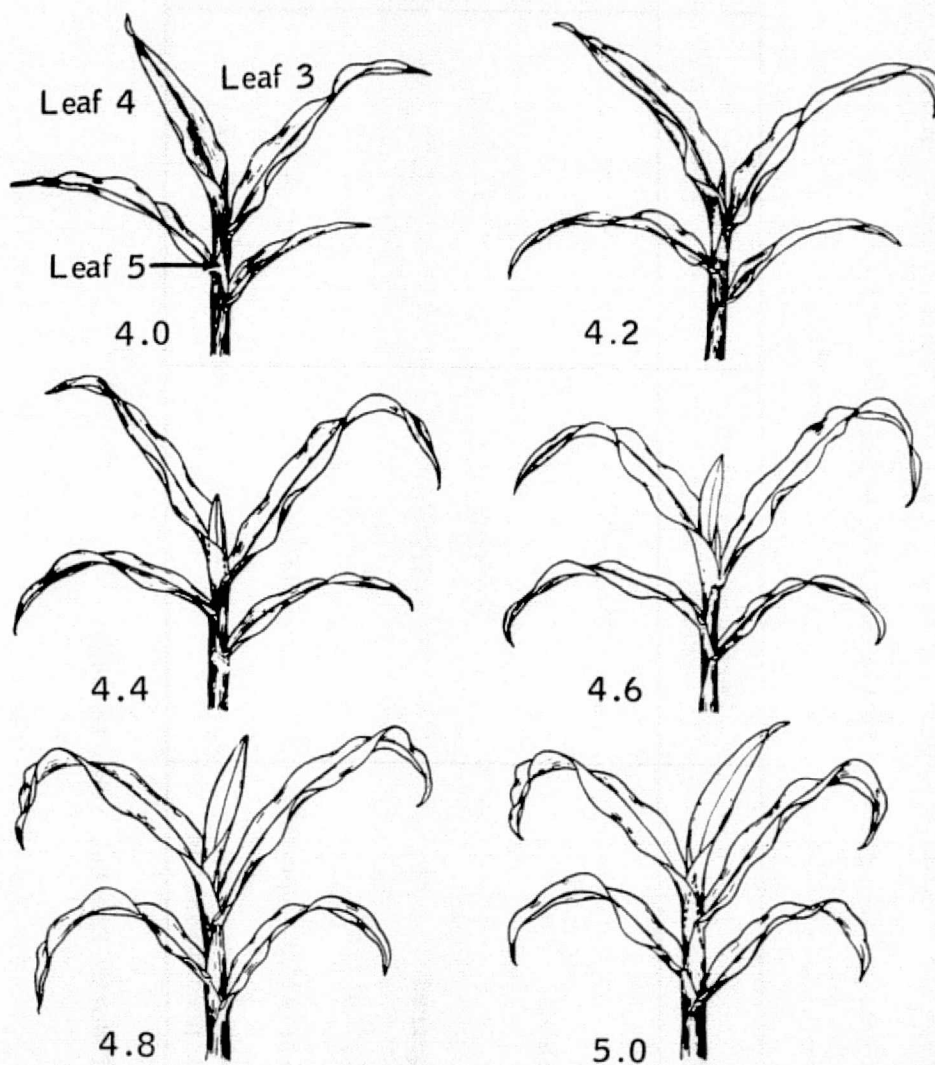[a]Counties of North Dakota, 1961 to 1967.

[b]In inches.

Figure 5-1.- Morphological development of the fifth leaf of corn showing five stages in the unfolding leaf.
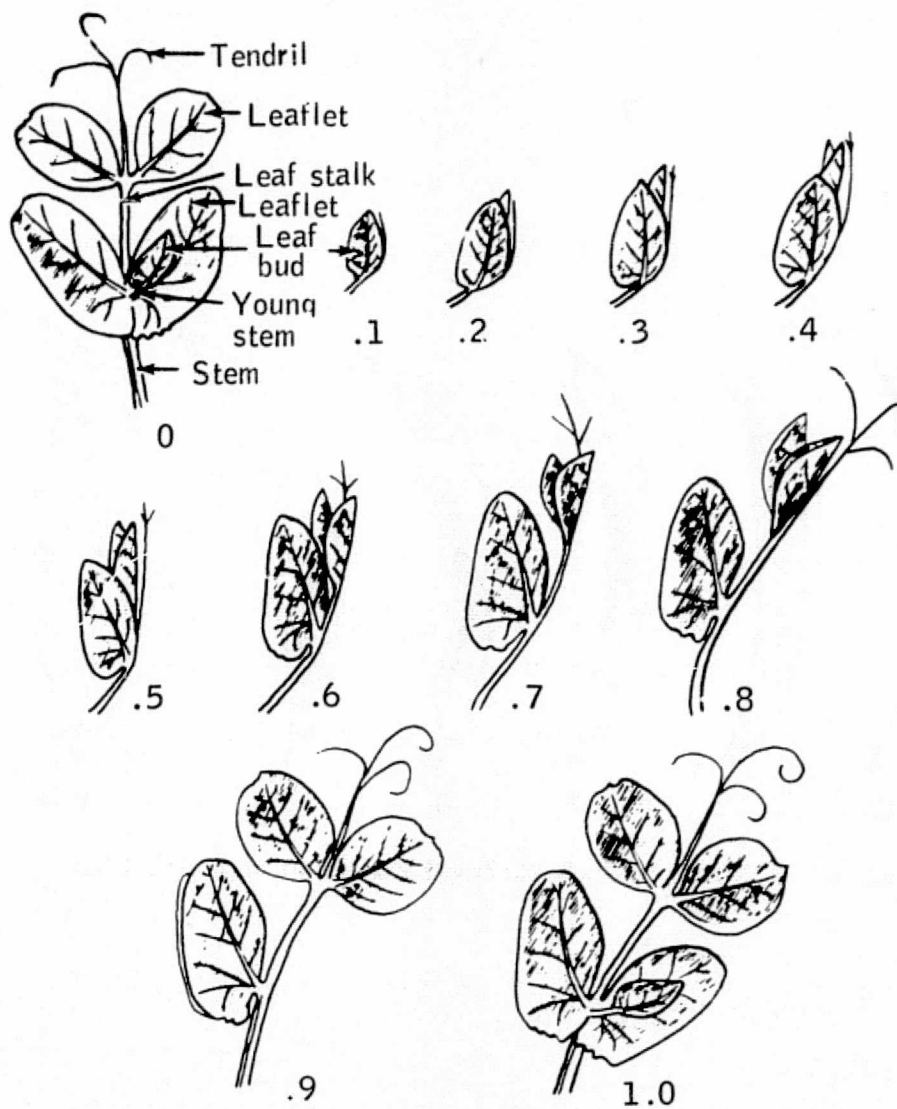
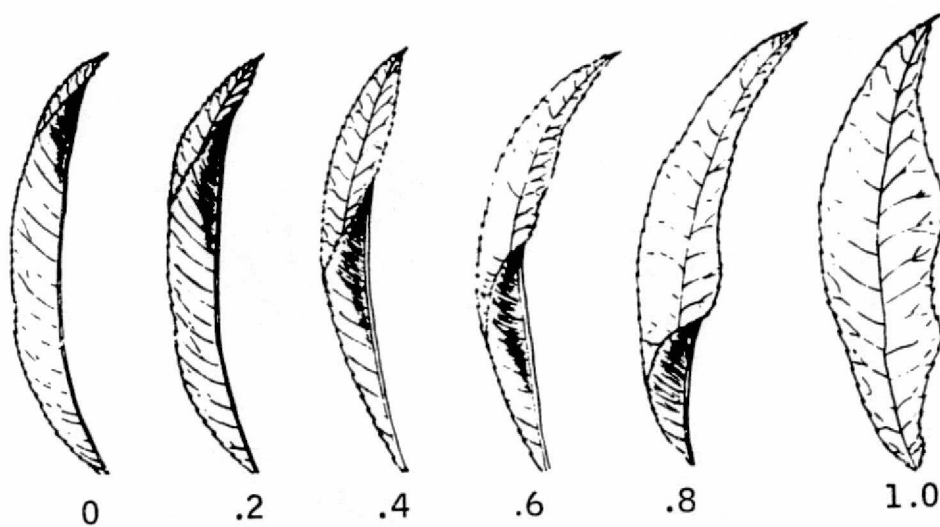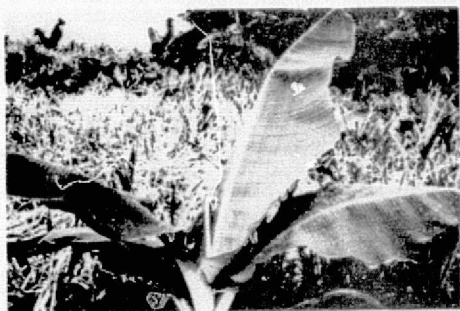Figure 5-2.- Morphological development of a garden pea (ref. 5-3).

Figure 5-3.- Morphological development of a peach leaf.

15.0

15.2

15.4

15.6
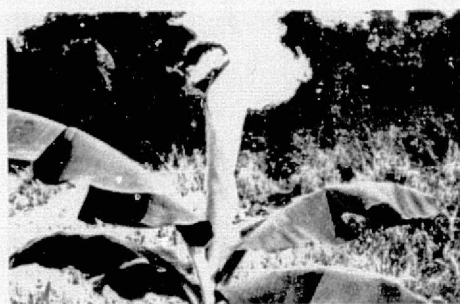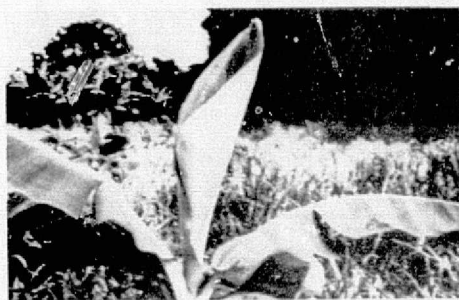
15.8

16.1

Figure 5-4.- Morphological development of the 16th leaf of banana.

First stage

Second stage

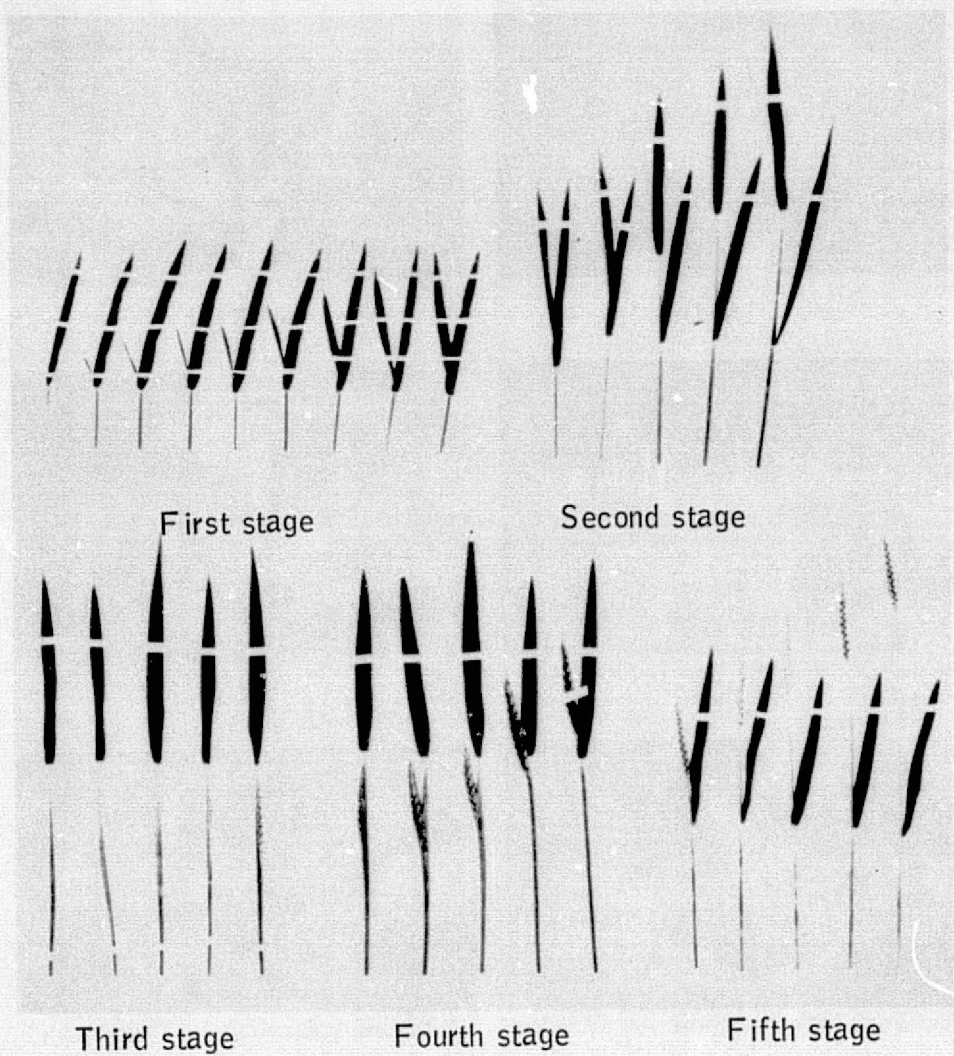Third stage

Fourth stage

Fifth stage

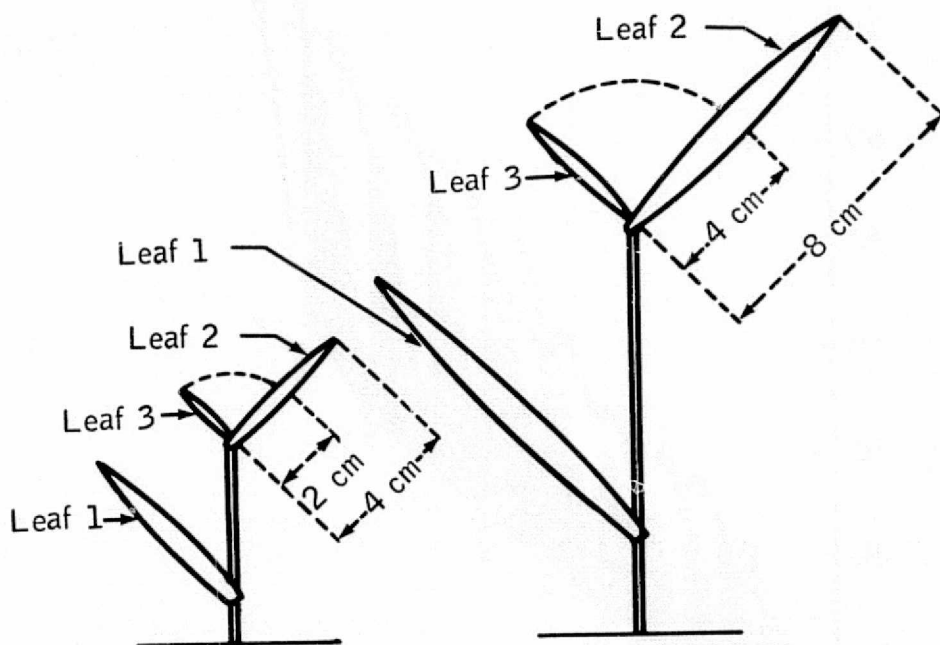Figure 5-5.- Morphological development of wheat (ref. 5-7).

Figure 5-6.– Diagrammatic illustration of plants having identical quantitative morphological indices (2.5) but different physical measurements. (From WMO Symposium on Agrometeorology of the Wheat Crop, Braunschweig, Germany, 1973.)
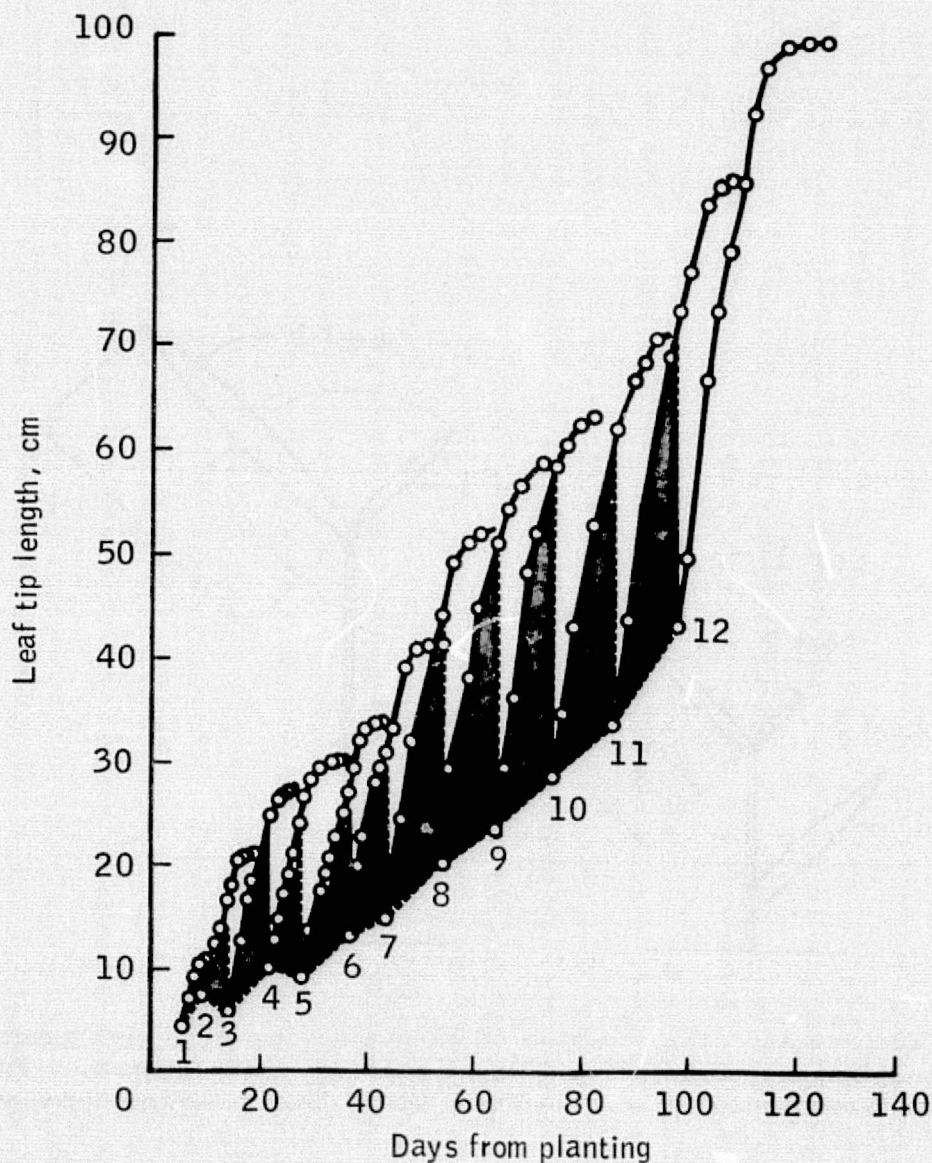
Figure 5-7.- Length-growth curve of a barley plant showing measurements of each successive leaf from appearance to termination of elongation. Shaded areas indicate the portion of growth curve that would be concurrent with quantitative morphological observations (ref. 5-4). (From WMO Symposium on Agrometeorology of the Wheat Crop, Braunschweig, Germany, 1973.)
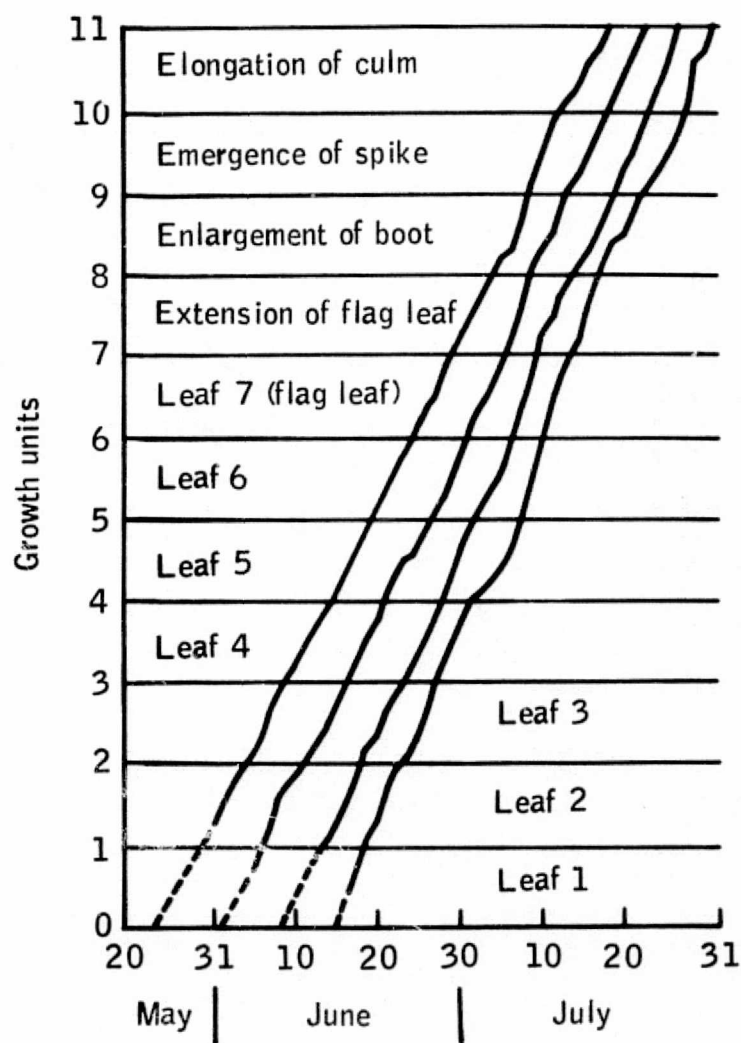
Figure 5-8.- Cumulative development of four plantings of Crim spring wheat at Dickinson, North Dakota, 1967. The broken line indicates time from emergence to beginning of daily observations (ref. 5-7).
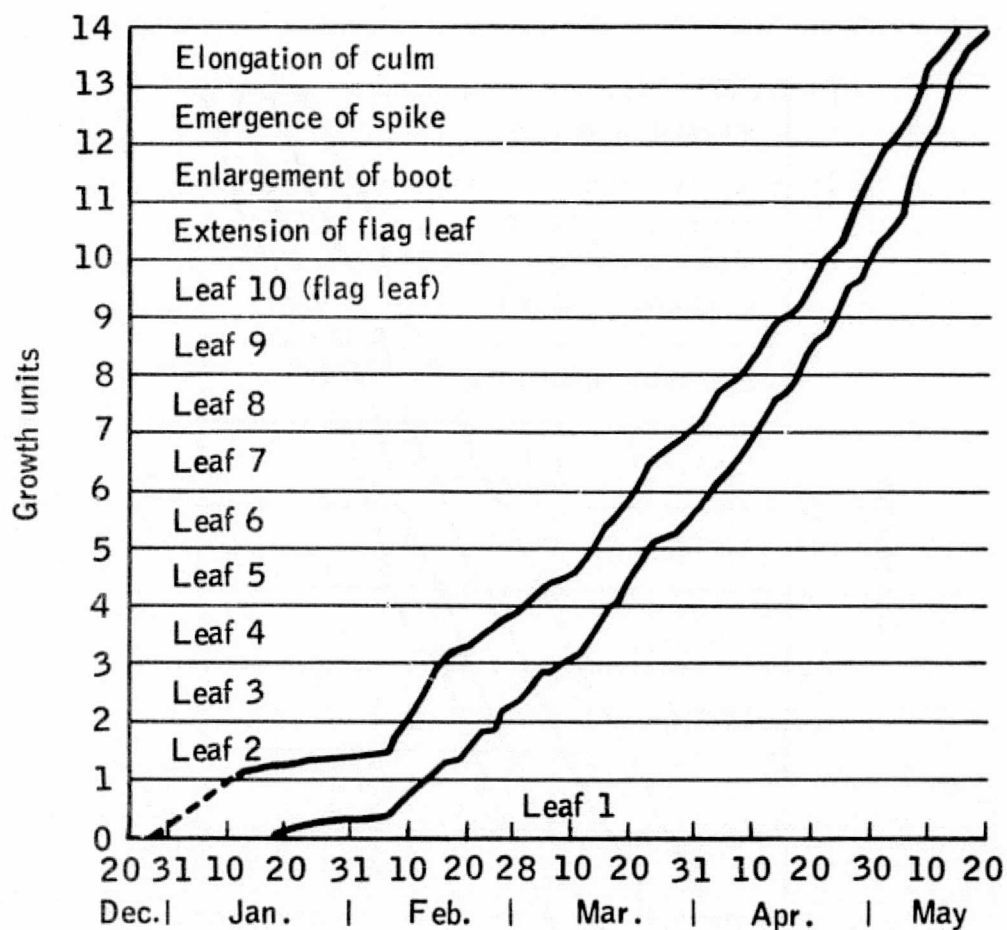
Figure 5-9.- Cumulative development of two plantings of Andnox winter wheat at Clemson, South Carolina, 1966. The broken line indicates time from emergence to beginning of daily observations (ref. 5-7).
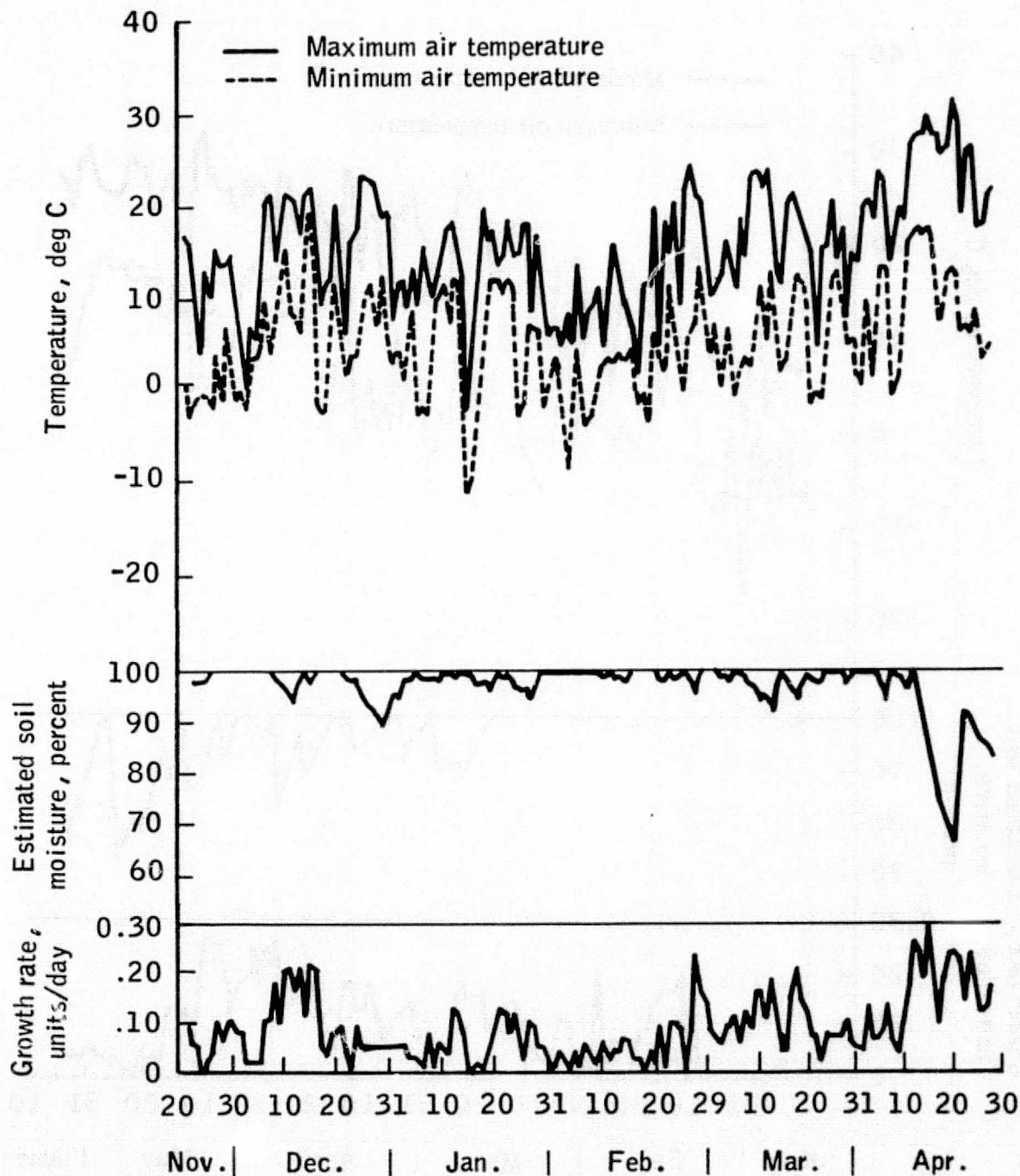
Figure 5-10.- Air temperature, soil moisture, and growth rate of Andnox winter wheat at Clemson, South Carolina, 1971-72, used in multiple-regression analyses. (From WMO Symposium on Agrometeorology of the Wheat Crop, Braunschweig, Germany, 1973.)
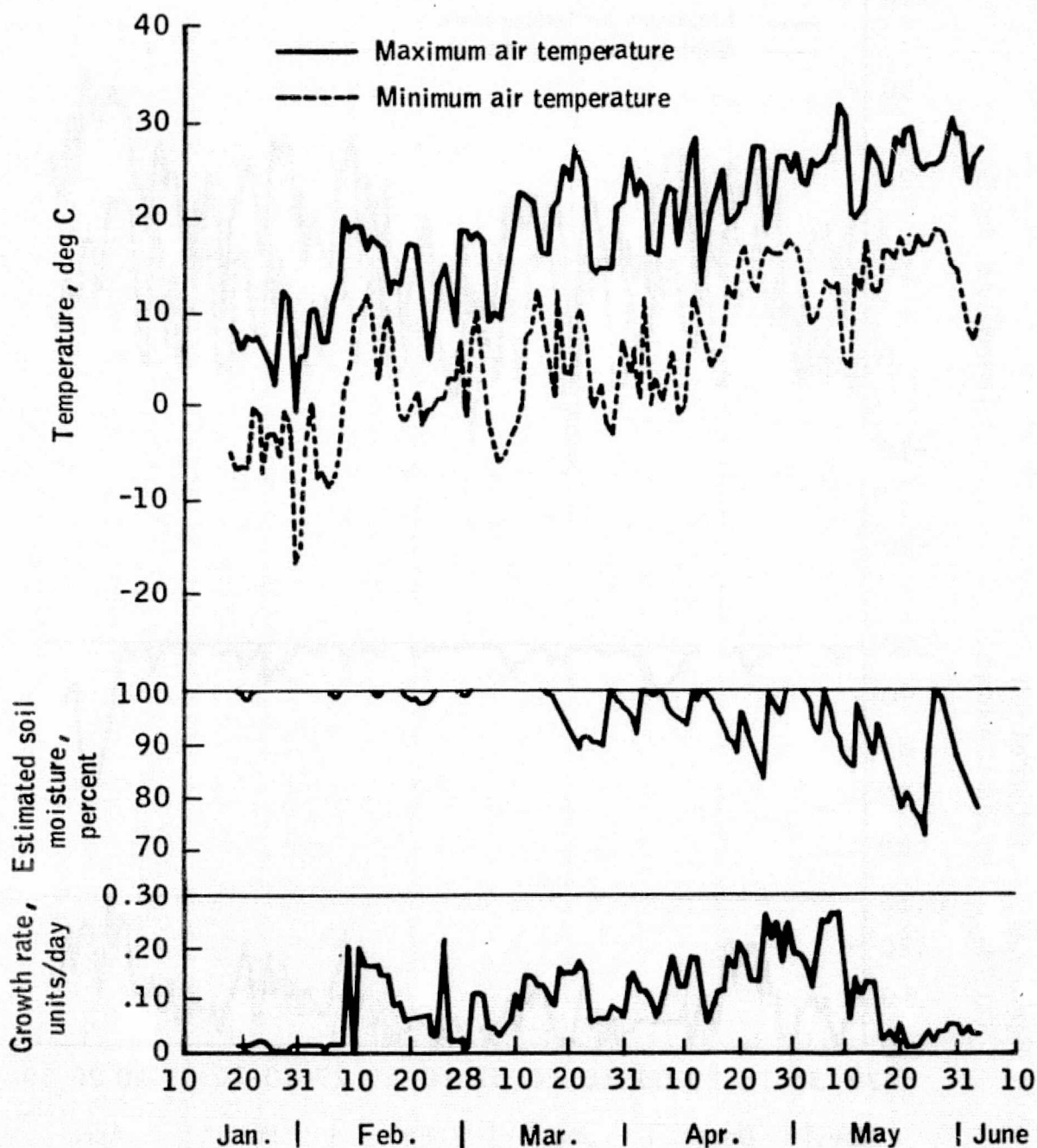
Figure 5-11.- Air temperature, soil moisture, and growth rate of Andnox winter wheat at Clemson, South Carolina, 1966, used in testing the prediction equation. (From WMO Symposium on Agrometeorology of the Wheat Crop, Braunschweig, Germany, 1973.)
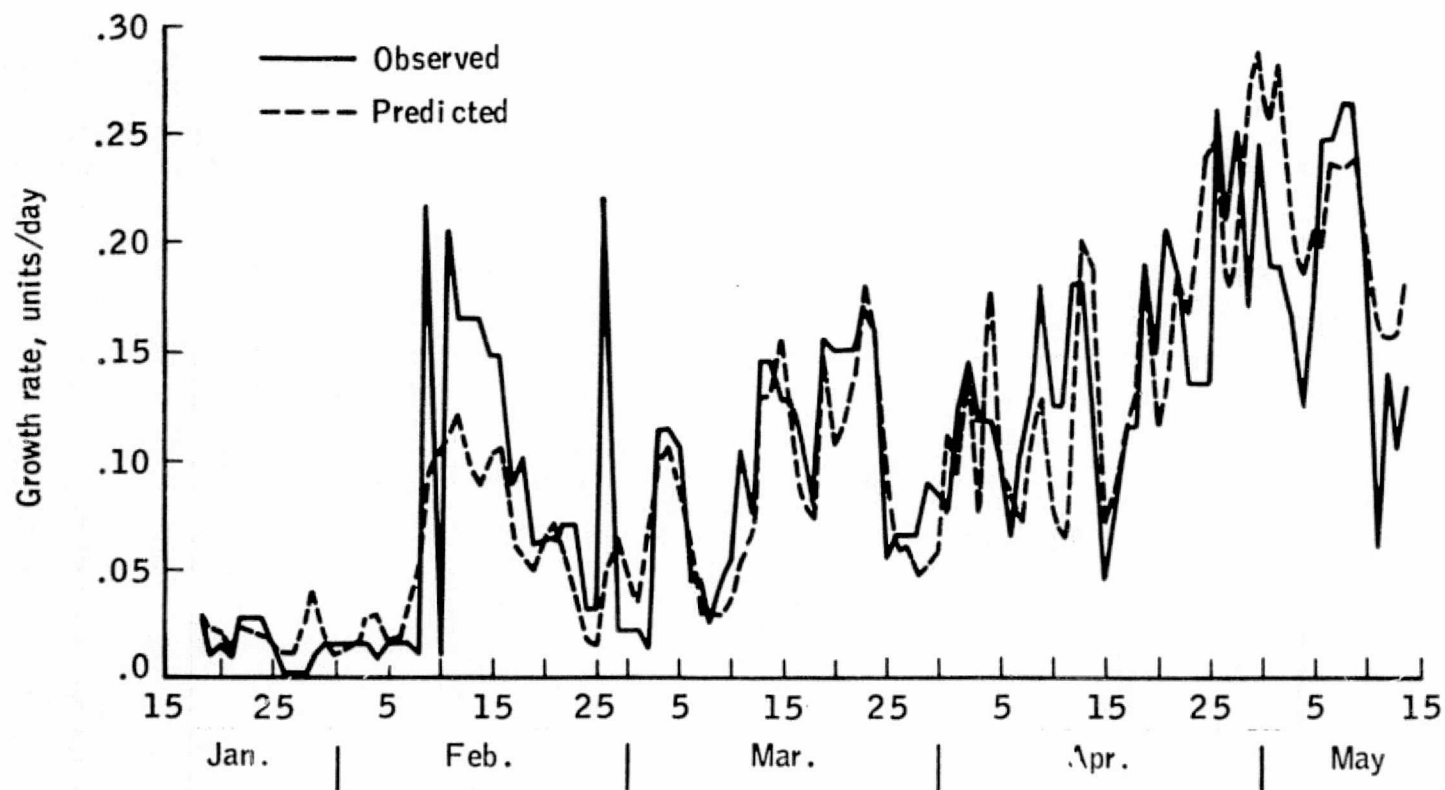
Figure 5-12.- Observed growth rate of winter wheat at Clemson, South Carolina, 1966, as compared to predicted growth rate obtained by an equation developed from growth and environmental data in 1971-72. (From WMO Symposium on Agrometeorology of the Wheat Crop, Braunschweig, Germany, 1973.)

Figure 5-13.- Observed growth rate of winter wheat at Clemson, South Carolina, 1966, as compared to
predicted growth rate obtained by an equation developed from growth and environmental data in
1971-72 (3-day running average). (From WMO Symposium on Agrometeorology of the Wheat Crop, Braun-
schweig, Germany, 1973.)

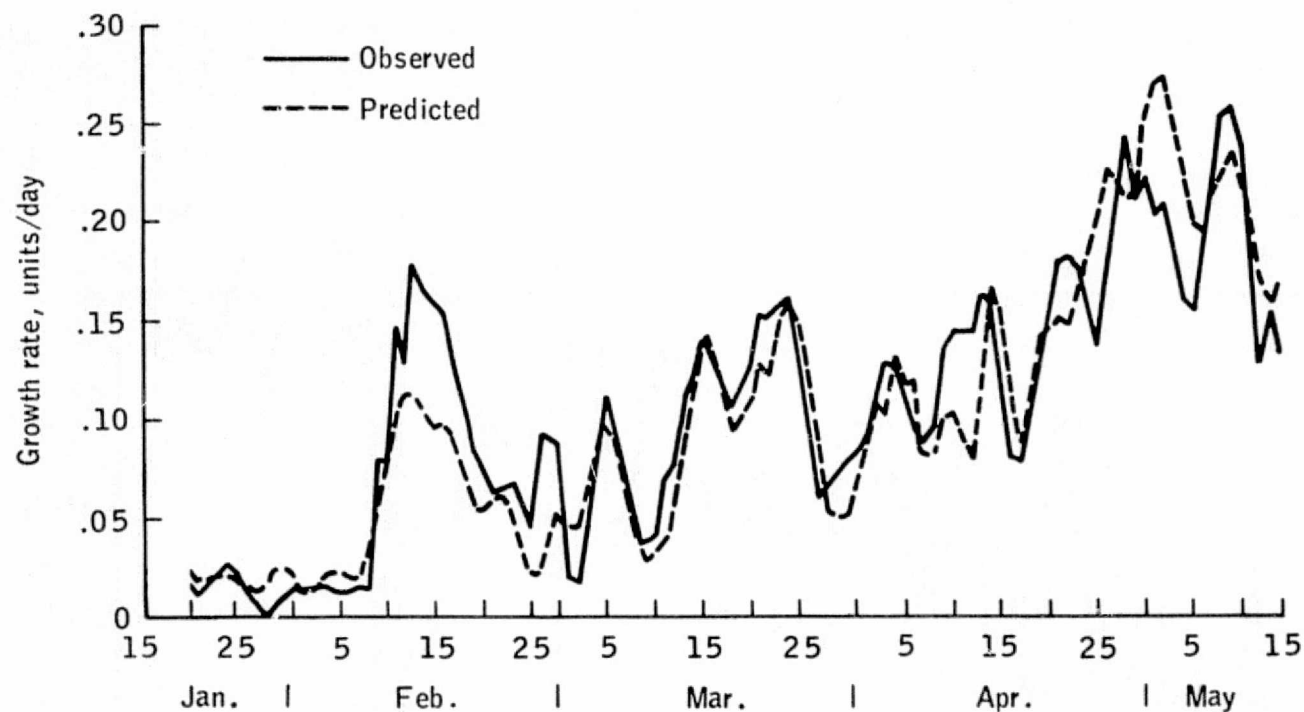$$\text{Previous EM} + \text{PCPN} - \left[\frac{(0.038TM_{10} - 1.28) \times DL_{10} \times \text{Previous EM}}{FC}\right] = \text{EM}$$

$$\sum \left\{ \begin{array}{l} EGR = -0.06495 + 0.000017(TX_{10})^2 + 0.0000385(TN_{10})^2 + 0.04434(EM) \\ \text{For periods: (1) May 2 to 11, (2) May 12 to 21, (3) May 22 to 31, (4) June 1 to 10,} \\ \text{and (5) June 11 to 20} \end{array} \right. +$$

$$\sum \left\{ \begin{array}{l} LGR = 0.30071 - 0.00283(TX_{10}) - 0.00191(TS_{10}) + 0.02633(EM)^2 \\ \text{For periods: (1) June 21 to 30, (2) July 1 to 10, (3) July 11 to 20, and (4) July 21 to 30} \end{array} \right. = \text{GI}$$

$$\text{Log } Y = -0.87249 + 2.42169(GI) + 0.35686(PP) - 0.37967(GI)^2 - 0.00841(PP)^2 - 0.09218(GI)(PP)$$

$e^{\text{Log } Y}$ = Predicted yield in bu/acre

DL – Day length, 12-hr
EGR – Early growth rate
EM – Estimated soil moisture, in.
FC – Field capacity, 4-in. average

GI – Growth index
LGR – Late growth rate
PCPN – Precipitation, in.
PP – Preseason precipitation, in.

TM – Mean air temperature, deg F
TN – Minimum air temperature, deg F
TS – Air temperature spread, deg F
TX – Maximum air temperature, deg F

Figure 5-14.– Prediction model of spring wheat yield.
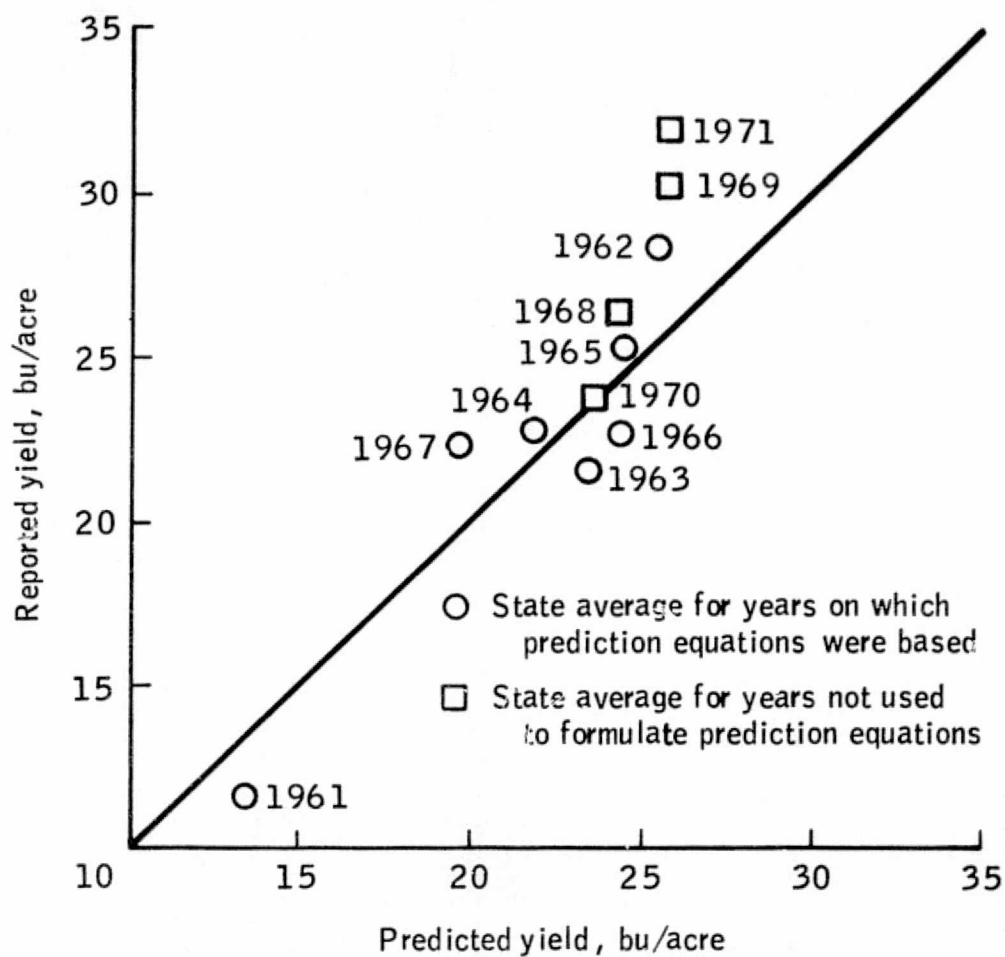
Figure 5-15.- Relationship of wheat yields reported for North Dakota to yields calculated by prediction equations.
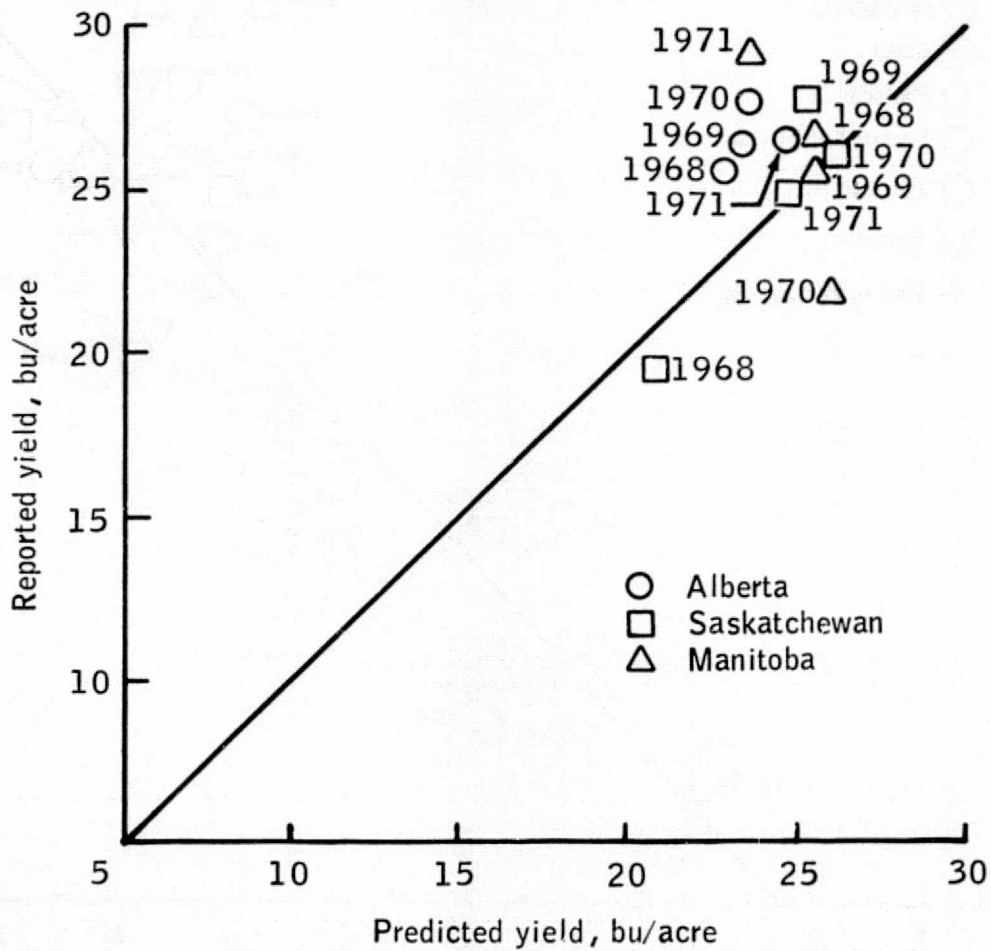
Figure 5-16.- Relationship of wheat yields reported for Canada to yields calculated by prediction equations.
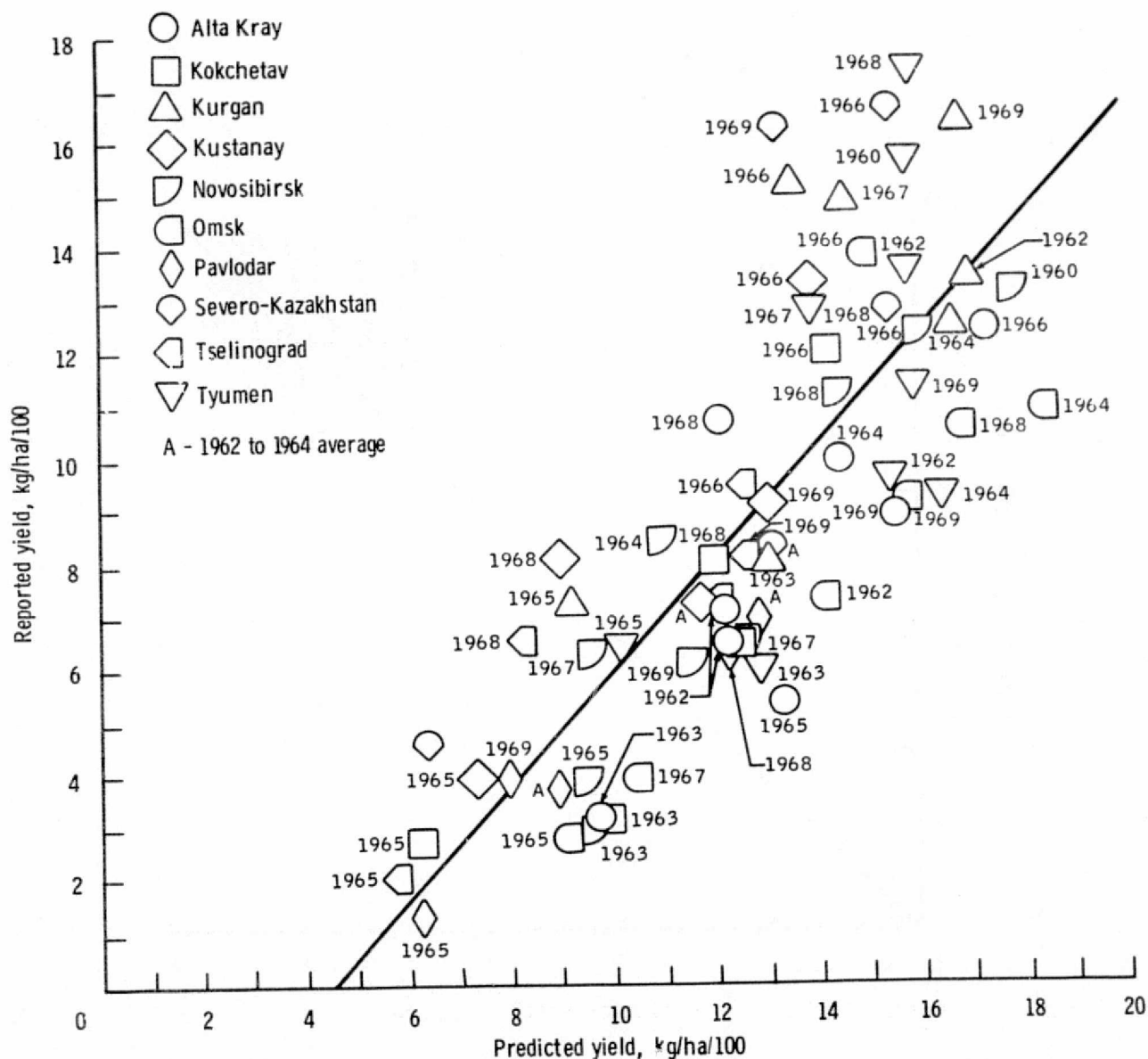
Figure 5-17.- Relationship of wheat yields reported for New Lands area of U.S.S.R. to yields calculated by prediction equations, where r is equal to 0.780, r required for significance at 1 percent is 0.311, and R^2 is equal to 0.608. Regression of reported yield Y on predicted yield X is represented as $Y = -4.687 + 1.064X$ (ref. 5-5).

Figure 5-18.- Relationship of average wheat yields reported for western Siberia and northern Kazakhstan to yields calculated by prediction equations (ref. 5-5).
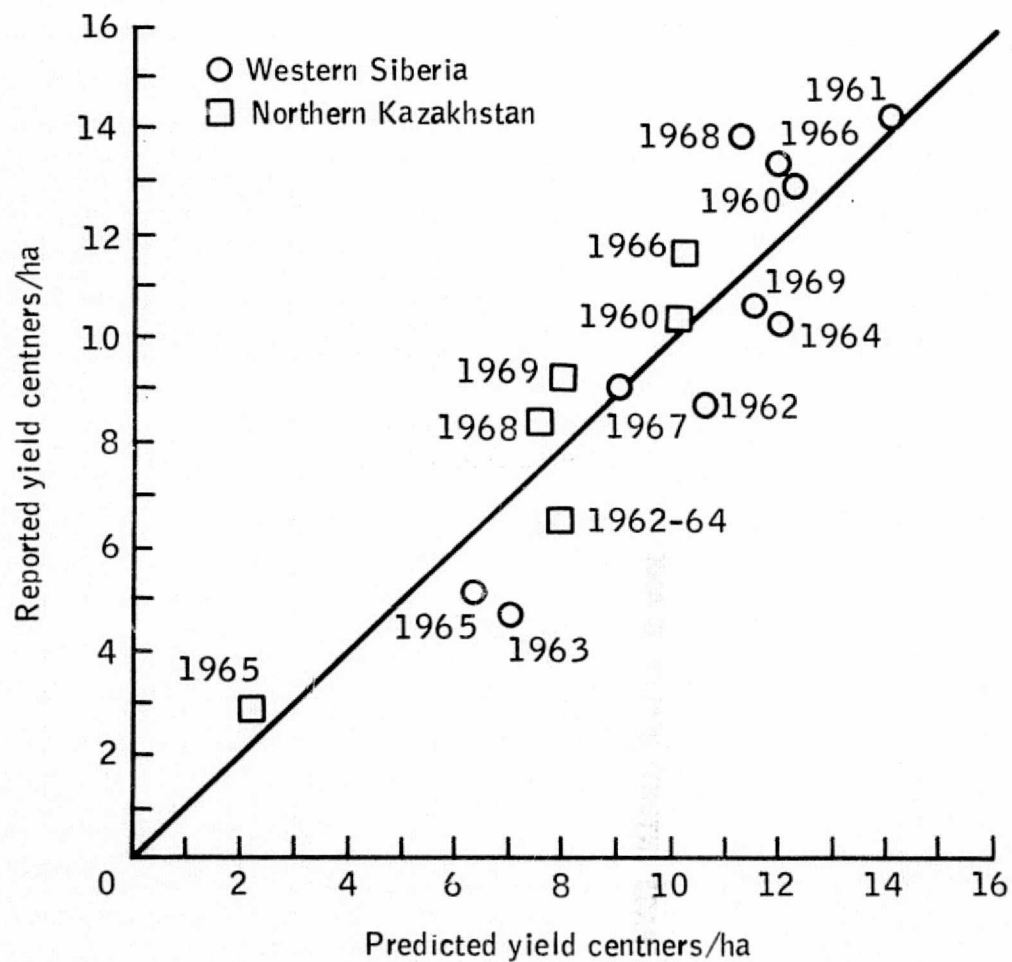
6. WEATHER/CROP MODELING IN THE U.S. DEPARTMENT OF AGRICULTURE

ECONOMIC RESEARCH SERVICE

By Rodney E. Steele*

Weather/crop-yield studies for foreign countries have been completed recently by the Economic Research Service (ERS) of the U.S. Department of Agriculture. The Foreign Demand and Competition Division of ERS has recently begun a weather/crop-production program to note the influence of weather on crop production around the world. Part of this effort involves developing predictive models for major grain-producing countries.

A weather/yield study of Argentine wheat is currently being conducted. Yield and weather data have been collected for the period from 1952 to 1973. The most readily available yield data are by province. However, these provinces vary considerably in size and climatic makeup. For example, the Buenos Aires province accounts for well over half the total wheat area and contains diverse climates. A single yield figure for this province is much more approximate than it is for other provinces. Smaller provinces would be preferable — that is, the equivalent of U.S. counties or of climatic subregions; however, the only data of this type are for a limited span of years ending with 1967.

Weather data limitations are perhaps more serious than yield data limitations. The weather data are obtained from station reporting, which the Argentine Government makes available through the auspices of the World Meteorological Organization (WMO). The data are issued on a monthly basis and consist of the average of daily mean temperatures and total precipitation. Argentina reports to the WMO better than many countries do, but numerous gaps exist for which no data were reported for particular stations; furthermore, the records for some stations have been kept for only the last few years. Only a few of the reporting stations are located within the principal growing areas. Seven stations have been selected; however, several of these stations are on the fringes of the wheat-growing area. Four stations are located in the Buenos Aires province. The average weather data from these climatically diverse areas may not adequately characterize the weather for the whole province.

The methodological approach in the Argentine study will be to relate weather and yields in a conventional multiple regression but to attempt different ways of relating the weather variables. One method will be to use the straight meteorological variables — monthly mean temperature and monthly precipitation — for the periods expected to have an influence on yields. Another

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approach might be to construct a weather index using some ratio of precipitation and temperature.

An ERS weather/yield study of Turkey was recently published (ref. 6-1). National wheat yields for the period from 1948 to 1968 and an aridity index, which is a ratio of monthly mean temperature and monthly precipitation, were used. After alternative equations were tested, January-February and May-June aridity indices and fertilizer consumption were used for the yield equation. The contributions of variables were significant, and the yield-equation multiple correlation coefficient was 0.82 with a standard error of estimate equivalent to approximately 10 percent of the mean yield. Weather data were used for only one station, Ankara, to represent national weather because poor results were obtained with regional weather and regional yields. Tests of forecasts for 1969-70 were very close to actual yields.

A former ERS analyst developed a wheat-yield prediction model for the U.S.S.R. The results are preliminary and have not been published. The yield and weather data included 27 weather regions from 1960 to 1971. Average weather for each region was derived from many reporting stations. Again, the weather data were monthly mean temperature and monthly precipitation. A soil moisture variable also was estimated by a simplified Thornthwaite formula. A rough measurement of fertilizer use or a time trend factor was included in most of the winter wheat regressions. Stepwise regression was used for each weather region. Because of the limited time series (12 years for most areas and only 7 years for several areas) and the consequent limited degrees of freedom, the specifications of the equations are of questionable value for prediction. The multiple correlation coefficients were generally high, mostly in the range from 0.80 to 0.97. The standard errors of estimate were generally better for the winter wheat equations, probably because of the strong trend factor. Measured relative to mean yields, the standard errors of estimate for the winter wheat regressions were generally in the 8- to 14-percent range; the standard errors of estimate for the spring wheat regressions were in the 10- to 25-percent range.

Another model for wheat-yield prediction in the U.S.S.R. used a different methodology to eliminate the problem of the limited time series. This model for spring wheat used yield data for 21 oblasts. The data for two sets of oblasts, grouped according to climatic similarity, were pooled over an 11-year period from 1960 to 1971. Weather variables similar to those of the previous U.S.S.R. study were used, except that accumulated preseason precipitation was used instead of soil moisture. Regression equations were estimated for use at three different stages of the crop season. An early model incorporated weather data through June; a middle model, through July 20; and a late model, through August. These equations were used to define a weather index — that is, the sum of the products of coefficients and the weather values. To estimate a predictive equation, the weather indices were regressed with yields by individual oblast. If significant at this point, a trend factor was included. Only 3 of the 21 oblasts had a significant trend factor. The multiple correlation coefficients of the oblast regressions varied considerably, but they were generally lower than those of the previous U.S.S.R. study; however, standard errors of estimate were of approximately the same magnitude. When aggregated with

area data to a production basis, the average prediction error for the 21 oblasts for the period from 1960 to 1970 was appproximately 12 percent for the early model, 9 percent for the middle model, and 8 percent for the late model. A test of predictions for 1971 produced errors on production of 7 percent for the early model, 3 percent for the middle model, and 4 percent for the late model. Wheat-yield prediction models were also made for the 1972 crop, but actual yield data were not available to permit evaluation. However, the models correctly predicted the record-low yields in the Volga area and the record-high yields in parts of western Siberia.

REFERENCE

6-1.   Coffing, Arthur: Forecasting Wheat Production in Turkey. Foreign Agricultural Economic Rept. no. 85, U.S. Dept. of Agriculture, Mar. 1973.

NICHOLS: What was the relative importance of the area in that total production model related to the yield?

STEELE: Are you speaking of the Turkey model?

NICHOLS: I am speaking of any model in which acreage is combined with yield to obtain a total production — that is, the relative importance of each.

STEELE: We used a yield-forecasting model, and the approach was simply to aggregate this yield into production rather than using yield as a variable in a production model.

NICHOLS: Is that verifying yield per unit area rather than total production?

STEELE: Yes.

HARTLEY: Instead of using your method of combining your oblast groups by just weighting them inversely to their variances, to weight them by the acres might be more appropriate to obtain something that is simulating the total production. When you are weighting yield-per-acre figures inversely to their variances, you may be weighting very highly the yield-per-acre figure that only applies to a small area. As a statistician, I have had experience with the tools that these statisticians apply to straight meteorological values; I think the method of step-up or stepdown gives completely different indices that are often not very relevant. We have to learn from people who are plant physiologists to combine the two methods. If you are trying to take many straight meteorological variables, the statistical techniques of stepwise regression are very volatile and untrustworthy. Secondly, multiple correlation coefficients depend on the degrees of freedom. You can have many multiple correlation coefficients, and you can have many degrees of freedom as long as your predictor variables are a small proportion of them. They have to refer to the tables. You see a multiple correlation coefficient of 0.9. This 0.9 may not mean a thing if three predictor variables and a thousand observations exist. I guess you would have to refer to the correlation coefficient in terms of the degrees of freedom available, which would be accessible.

STEELE: Yes, I recognize those objections, and I share most of the points that you made. The technique of pooling time series and cross sectional data and increasing the degrees of freedom to get lower multiple correlation coefficients is preferable to the other study that entailed 12 years but used just the straight time series regression.

7. WINTER WHEAT: A MODEL FOR FORAGE AND GRAIN

By Ed W. Chin Choy,* H. Doug Jose,[†] and John F. Stone*

Only one known grain- and forage-production model for winter wheat is available at present. The available grain-yield prediction equations (refs. 7-1 and 7-2) are correlative; thus, they are of questionable usage in predicting. The purpose of this model is to enable consideration of various combinations of forage and grain production that would result in economic optimization. This optimization is necessary because winter wheat is used for both winter and spring pasture and grain production on more than 6 million acres in Oklahoma alone.

SUBMODELS

The model is deterministic. The first-order causes for wheat development and production were considered, and, upon inspection of the available data, the following variables were used: climatic (temperature and rainfall) and edaphic (soil moisture characteristics). The rainfall/soil moisture characteristics were coupled with runoff and soil drainage equations. Plant response (production) due to these environmental conditions was calculated in forage and grain submodels.

Forage Submodel

The idealized accumulation of dry matter as a function of time can be seen in figure 7-1. Implicit in this curve is the phenological development of the plant. For convenience, figure 7-1 is described by two equations, the exponential and monomolecular functions. The exponential growth curve (eq. (7-1)) was used from planting to jointing, and the monomolecular equation (eq. (7-2)) was used from jointing to the end of the season (ref. 7-3).

$$Y_t = rY_{t-1} \qquad (7-1)$$

$$Y_t = MS^d\left(s^{-1} - 1\right) \qquad (7-2)$$

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*Oklahoma State University, Stillwater, Oklahoma.
[†]University of Saskatchewan, Saskatchewan, Canada.

where Y_t is the amount of dry matter accumulated on a specific day, Y_{t-1} is the previously accumulated dry matter, M is the estimated maximum dry matter production possible for any day (1500 lb/acre), d is the number of days after April 15 (jointing), and r and s are constants. Thus, the value of Y_t or Y_{t-1} is dependent on daily plant growth and plant depletion due to livestock consumption.

Grain Submodel

A simple linear regression between yield and forage production was used (refs. 7-4 and 7-5). The equation was of the form

$$\text{Yield (bu/acre)} = 11.443 + 0.005 \text{ (lb/acre dry matter)} \qquad (7\text{-}3)$$

The amount of dry matter accumulated is that present at anthesis. At anthesis, the plants are assumed to be in the reproductive stage; hence, they are static in growth.

Climate Submodel

The climate submodel consisted of temperature and precipitation variables. The effect of temperature on growth, assuming light is nonrestricting, is related to the plant enzymatic activity. This characterization is expressed as the Q_{10} of the plant and is shown in figure 7-2. Maximum daily temperatures were used in computing the growth.

Because supplemental irrigation is not commonly practiced in the majority of the wheat-growing areas of Oklahoma, the primary input for soil moisture was precipitation. No runoff was assumed when precipitation was in the form of snow. When precipitation was in the form of rainfall, the following runoff equations were used.

$$\text{Runoff} = 1.9 \times 10^{-4} \exp\left(2.94 \times \text{AMI}\right) \qquad (7\text{-}4)$$

when 0.7 inch $\leq$ AMI $\leq$ 2.0 inches, and

$$\text{Runoff} = 0.34 + 0.204 \text{AMI} \qquad (7\text{-}5)$$

when AMI > 2.0 inches, where AMI is the antecedent moisture index of the soil and is dependent on the soil moisture condition and the periods between rainfall. Runoff computations using these equations compared favorably with

7-2

those of the U.S. Department of Agriculture Soil Conservation Service (ref. 7-6) for class I soils of north-central and northwest Oklahoma.

Soil Moisture Submodel

The climatic variables that were used were obtained from the National Weather Service. Soil moisture status was calculated from the following water balance equation.

$$S_t = S_{t-1} + P_t - R_t - D_t - ET_t \qquad (7\text{-}6)$$

where t is a specific day, $t-1$ is the preceding day, S is the soil moisture of the top 4 feet of the soil profile, P is the precipitation, R is the runoff from the precipitation, D is the drainage of soil water from the profile, and ET is the evapotranspiration of the crop. The unit of these parameters is inches. Rainfall and runoff have been previously defined, and D and ET are unknowns.

In most studies of ET, the value of D is usually confounded with ET and called consumptive use. The magnitude of the ratio of these terms varies throughout the growing season; hence, to separate the values of these variables is necessary. The ET was calculated as a function of pan evaporation and growth. Because observation of pan evaporation is limited to the warmer months of the year, the Blaney-Criddle (ref. 7-7) method was used to approximate pan evaporation when pan evaporation was unavailable. Preliminary studies indicated that this method is as good as any other method for Oklahoma conditions. The relationship between ET and pan evaporation was dependent on the amount of dry matter that had accumulated.

The drainage component was functionally dependent on the amount of soil moisture in the profile and the stage of crop growth. For the fallow season (June to September), the change of soil moisture in the soil profile is primarily due to drainage, but evaporation is important after a precipitation event. During the spring season (February to June), transpiration is important, and drainage is assumed to be negligible. The equation used for drainage is

$$\text{Drainage} = 0.1 \times \exp(2.0 \times \text{available water}) \qquad (7\text{-}7)$$

The previous equation is based on data presented in reference 7-8.

The soil profile is treated as a reservoir from which drainage and evapotranspiration withdrawals are made (eq. (7-6)). The capacity of the reservoir is normally defined as available water or extractable water with limits at field capacity (a pressure of 0.33 bar) and at permanent wilting percentage (PWP) (a pressure of 15 bars). Examples of this usage can be seen in the work

of Shaw (ref. 7-9) and Baier and Robertson (ref. 7-10). When the amount of
water in the soil profile is at field capacity, the soil is assumed to be satu-
rated; thus, any additional rainfall is regarded as runoff and is not added to
the soil profile. Ritchie's (ref. 7-11) relationship between growth and soil
moisture was used in the calculation of incremental growth (table 7-I).

THE MAIN PROGRAM

The main program of the model interfaced the subprograms in a multiplica-
tive fashion. Hence, the interaction of soil moisture and temperature in equa-
tions (7-1) and (7-2) can be expressed as

$$Y_t = (a\sigma)(b\tau)(F)(R)\left(Y_{t-1}\right) \tag{7-8}$$

$$Y_t = (a\sigma)(b\tau)(F)(M)\left(R^D\right)\left(R^{-1} - 1\right) \tag{7-9}$$

where σ is the soil moisture coefficient (from table 7-I), τ is the temper-
ature coefficient (from fig. 7-2), and F is the soil fertility factor. The
coefficients a and b are constants assigned to cultivars. Because of
present-day lack of knowledge on the movement, availability, and interaction of
nutrients, the soil fertility factor F was assumed to be constant between
and within years. Because the cultivar used in this analysis was constant —
Triumph-type wheat — equations (7-8) and (7-9) could be reduced to

$$Y_t = \sigma\tau C Y_{t-1} \tag{7-10}$$

$$Y_t = \sigma\tau M C^D\left(C^{-1} - 1\right) \tag{7-11}$$

where C is the combination of constants of equations (7-8) and (7-9). It
should be noted that the numerical value of C is not the same for equations
(7-10) and (7-11).

The concept behind the multiplicative scheme is that growth will occur
ideally only if both temperature and soil moisture are nonrestrictive (ideal
growing conditions). Under field conditions, especially under dryland condi-
tions, soil moisture becomes the limiting factor; hence, the multiplicative
scheme reduces the amount of growth possible in accordance with limitations
imposed by environmental conditions for the day. A 1-day lag time was built
into the program when either soil moisture or temperature conditions prevented
growth.

RESULTS

Validation of Soil Moisture Model

Historical data were available for testing the soil moisture program independently from the data used in calculating the soil moisture parameters. The measured soil moisture, which is obtained by the neutron scatter method, is the average of several test plots for that area. If the soil moisture model were truly predictive, initiating the value of S_t at a specific time would predict with reasonable accuracy the soil moisture content for several years without redefinition of S_t. The comparisons are shown in table 7-II. The soil moisture model fitted the actual data reasonably well. The model consistently overestimated soil moisture at the end of growing season; investigation of this fact showed that the field water content was always less than that of the pressure of 15 bars soil water potential. This information raises the question of usage of the pressure of 15 bars moisture content as the PWP for this soil.

Validation of the Forage Model

Like the soil moisture model, the forage model was validated from areas where the climate parameters were obtained. The comparison between computer-simulated and measured forage is shown in table 7-III. The measured forage production represented all straw material present at harvest and may be slightly misleading because the water content of the straw was unknown; however, the computer-simulated value assumed a 15-percent water content of the forage. Also, the model was generalized for countywide prediction, whereas the measured values were from small test plots in which a sampling error was confounded. However, qualitative comparisons of the results of computer simulation and the past memory of field personnel add credence to the forage predictability of the model.

The comparison between test-plot yield and computed yield is also illustrated in table 7-III. Again, the prediction of the model was comparable to the measured field values, using the same caution for grain yield as that applied to forage. On a four-county basis on the Grant-Pond Creek soil complex, the prediction of the model was off by less than 10 percent for the years of simulation.

CONCLUDING REMARKS

To use a model for prediction purposes, the independent variables in the model should be directly related to the dependent variables. When no direct relationship (correlation) exists between the variables, the validity of the model is questionable, regardless of statistical manipulation.

The model was tested on only 3 years of available data; it was only on data from these 3 years that the fertility assumption could be confidently made. Little is known about the effects of daily nutrient availability and its action on plants under field conditions. If nitrogen, potassium, and phosphorus were independent of each other in plant nutrition, no problem would be encountered in plant tissue analysis.

The soil moisture model of growth function seems to be adequate in the prediction of forage growth. As previously mentioned, soil moisture was continuously computed for 4 years for both fallow and production periods without interrupting the program. The three measurements per year approximately coincided with planting, spring growth, and postharvest. Except for the postharvest readings, the computer-simulated values closely matched the measured values. Investigations into the values obtained for the postharvest period indicated that the soil moisture for the lower depths of the soil profile (12 to 36 inches) was far below the plant PWP pressure of 15 bars water content. This result questions the usage of this soil moisture parameter for wheat in the Great Plains. The present model integrates the fields of plant and soil sciences as much as possible. This deterministic model is based on primary cause-and-effect relationships that are based on physical parameters.

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QUESTIONS AND ANSWERS

BARGER: How do you define PWP?

CHIN CHOY: The PWP is permanent wilting percentage, which is commonly accepted
as a pressure of 15 bars atmosphere; however, it is now known to be
different within varieties for various crops. For example, the
classical study of Veihmeyer and Hendrickson judiciously used a
variety of sunflower that wilted at exactly 15 bars. Had a differ-
ent variety of sunflower been used, the result would have been dif-
ferent.

BARGER: But PWP is the lower limit of available soil moisture?

CHIN CHOY: The PWP is by definition the lower limit of available soil moisture.

BARGER: Could PWP be as much as 50 bars?

CHIN CHOY: The PWP could be 50 bars. In certain desert plants, it is as much
as 60 bars.

HARTLEY: In figure 7-1, was the growth during a particular period or
throughout the period?

CHIN CHOY: Growth was throughout the entire period.

HARTLEY: What was the duration of growth?

CHIN CHOY: The growth was up to May 30.

HARTLEY: Are you speaking of total growth?

CHIN CHOY: Total growth is correct. The exponential and monomolecular func-
tions were used.

HARTLEY: Was the moisture also cumulative?

CHIN CHOY: Yes.

HARTLEY: This fact would not indicate whether the moisture was deficient
during part of the period?

CHIN CHOY: In any one period, we look at our temperature and our soil moisture.
We put in our coefficients there, a Q_{10} for temperature and
available moisture. We then multiply those. Under ideal condi-
tions, the multiplication is 1. If either temperature or available
moisture is not optimum, you will obtain a value less than 1.

7-8

HARTLEY: You are preferring to do that for cumulative data up to a particular time rather than for time intervals?

CHIN CHOY: The period (time increment) that was used in the model was 1 day. Hence, calculations were made on a day-to-day basis with the cumulation of dry matter and water use computed daily. Ultimately, we broke the period into time intervals because we were grazing cattle on the wheat. The farmer needs to know by March 1 whether or not to sell his cattle that he stocked in November.

ROBERTSON: If I understood the speaker correctly, he said that he found that mean daily temperature was as effective as using maximum and minimum temperatures.

CHIN CHOY: No.

ROBERTSON: No? Then I misunderstood you.

CHIN CHOY: Mean daily temperature reflects an hourly value. The average hourly value was equivalent to the average temperature.

ROBERTSON: Why did you not use available minimum temperature and maximum temperature separately. My feeling is that you get much more information if you use these two elements separately rather than using a daily mean.

CHIN CHOY: To obtain verification of temperature, we had to use a mean because of lack of information.

TABLE 7-I.- THE RELATIONSHIP BETWEEN GROWTH AND SOIL MOISTURE

Available water, percent	Growth, percent
<20	0
20 to 80	$-33.33 + 1.67 \times$ available water
>80	100

TABLE 7-II.— A COMPARISON OF MEASURED AND COMPUTER-SIMULATED

SOIL MOISTURE[a]

[Top 4 feet of soil profile]

Date	Measured value, in.	Computed value, in.
Oct. 20, 1958	9.28	9.97
Mar. 19, 1959	7.68	7.35
June 25, 1959	6.92	7.50
Nov. 9, 1959	10.72	10.00
Apr. 5, 1960	10.59	8.78
June 22, 1960	[b]7.21	9.08
Sept. 28, 1960	10.02	10.40
Mar. 14, 1961	8.11	7.67
June 26, 1961	[b]7.19	9.24
Sept. 28, 1961	9.05	10.74
Mar. 15, 1962	9.46	7.56
June 19, 1962	[b]6.77	9.24

[a]Cherokee, Oklahoma, 1958 to 1962.

[b]The discrepancy between the measured and computed values was primarily because the laboratory PWP value (a pressure of 15 bars gravimetrically determined soil water potential) was higher than the values measured in the field.

TABLE 7-III.- A COMPARISON OF MEASURED AND COMPUTER-SIMULATED

GRAIN AND FORAGE PRODUCTION[a]

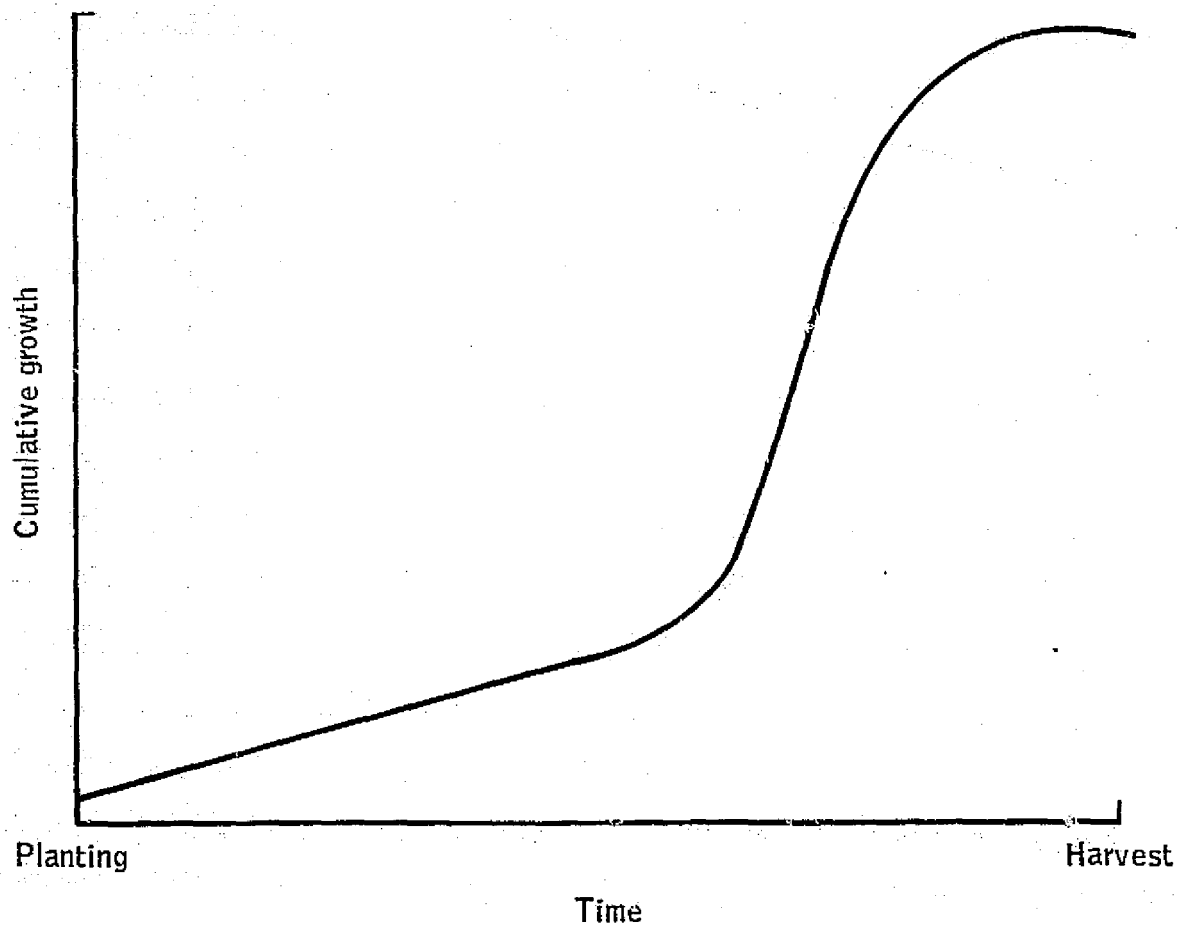| Year	Forage, lb dry matter/acre		Grain, bu/acre	
	Measured	Computed	Measured	Computed
1960	6249	4897	42.0	44.6
1961	6891	6991	46.0	46.2
1962	3635	2761	33.8	29.7

[a]Cherokee, Oklahoma.

Figure 7-1.- The idealized accumulation of dry matter as a function of time.
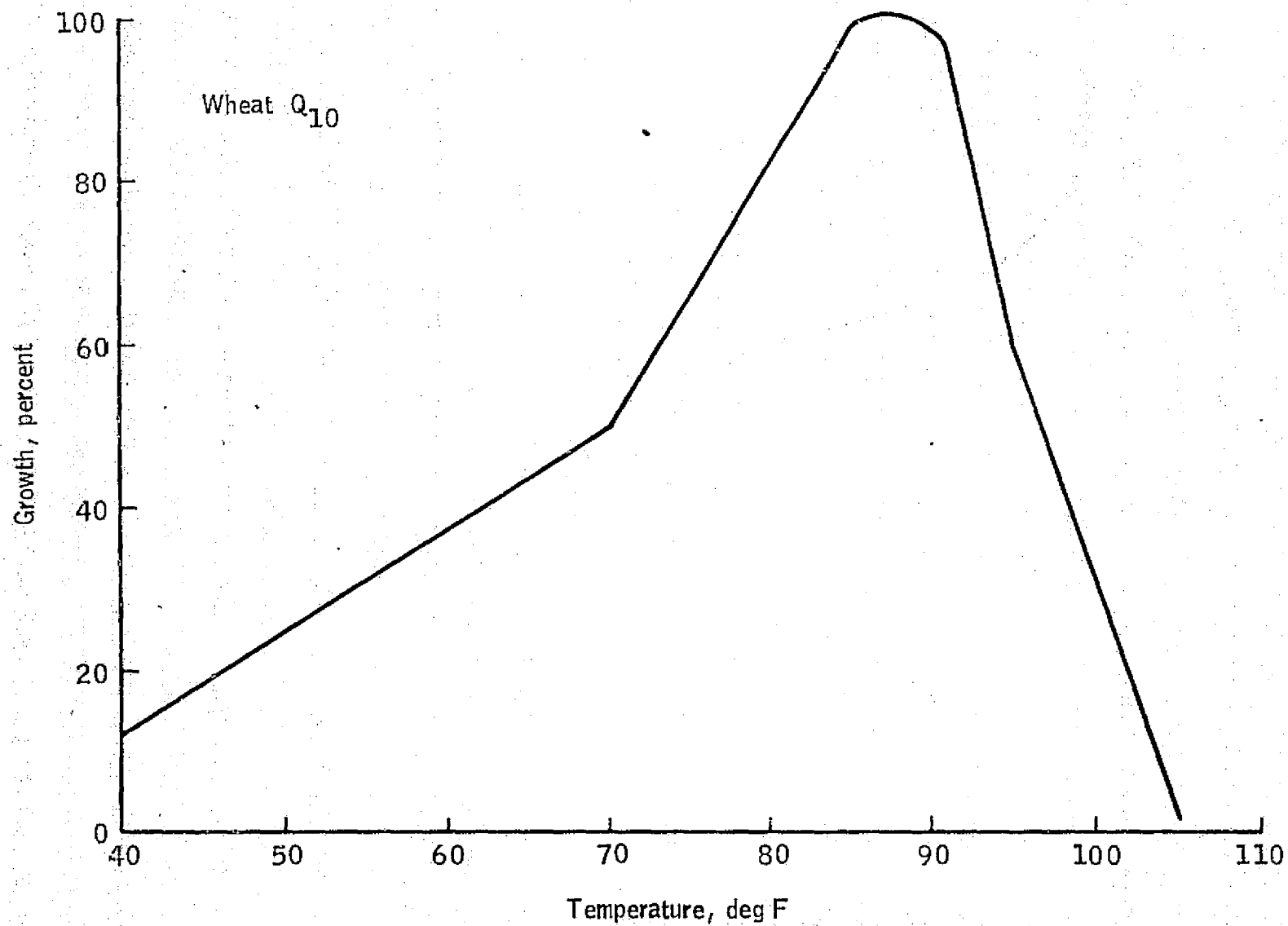
Figure 7-2.— The effect of temperature on growth Q_{10}.

8. A MODEL OF GLOBAL WHEAT PRODUCTIVITY:

U.S. SPRING WHEAT

Richard Tracy,[*] Linda Buttel,[†] Thomas Phillips,[†] Paul Cox,[†] and Lois Wood[†]

Two worldwide events are of such proportions that many people feel they forecast certain and widespread catastrophe for the human population: the explosive growth of global human population (ref. 8-1) and the recent changes in global climate (ref. 8-2). Recent changes in climate have resulted in large-scale famine and hardship in some regions of the world (ref. 8-3); however, crop yields in other regions have significantly benefited from recent climate changes. Despite these obvious climatic perturbations of the food production system, the significance of these perturbations in terms of the overall food budget of the world is not yet obvious.

The Climate and Food Project at the University of Wisconsin has been established to study and model the dynamic aspects of world climate and climatic effects on the food production system. Initial attention has been concerned with a study of global wheat production.

MODEL FORM

The climatological modeling goal of the Climate and Food Project is to predict mean monthly temperatures and precipitation for enough worldwide geographic points to construct a crude synoptic pattern of these means from 1 to 24 months in advance. Therefore, the prediction of global food yield necessitates constraining the food-yield modeling efforts to the use of mean monthly climate data as independent inputs to the models. To build models of a global scale that work at a biologically mechanistic cause-and-effect level is virtually impossible. Thus, the approach has been to search for statistical models of crop yield that are correlated with the mechanisms of plant growth.

The wheat plant basically requires definable proportions of moisture, energy, nutrients, and freedom from disease to attain optimum yield. Moisture available for wheat growth is almost always in the form of soil moisture, which, if not measured, can be predicted from a soil water budget model that reflects the amount of rainfall input to the soil, the soil water-holding capacity, and the many environmental variables associated with

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[†]University of Wisconsin, Madison, Wisconsin.

evapotranspiration (wind, relative humidity, air temperature, solar radiation, and others). Temperature has a somewhat stereotyped effect on plant growth for well-watered plants (fig. 8-1(a)), which generally reflect temperature influences on the biochemical reactions associated with growth (ref. 8-4). Therefore, increased temperature and all factors that contribute to the heat load on the plant can simultaneously enhance plant growth by speeding biochemical reactions and impede plant growth by enhancing evapotranspiration, thus removing water from its availability to the photosynthetic process. This complex interaction implies that the optimum temperature for plant growth may well depend on the level of soil moisture — that is, when abundant soil moisture exists, the optimum temperature for plant growth is expected to be closer to the optimum temperature for biochemical processes, which is ordinarily a high temperature. However, if the soil moisture is very low, optimum growth will occur at generally lower temperatures at which the plant can optimally use the limited water resource. Therefore, if the optimum temperature for plant growth is a function of soil moisture and if the maximum plant growth is limited by the rates of biochemical processes, plant-growth-rate curves similar to those depicted in figure 8-1(b) should be expected. This hypothetical interrelationship of soil moisture, temperature, and plant growth rate is also suggested by the data in figure 8-2, which show the relationship of temperature, rainfall (a correlate to soil moisture), and wheat yield (a correlate to plant growth rate) for North Dakota.

If the optimum temperature peak for wheat yield is not constant and depends on the complex of variables that ultimately influence moisture availability to the plant, then no model exclusively involving means of temperatures and precipitation as independent variables can describe wheat yield, because of the widely varying global climatic and edaphic conditions under which wheat is grown. Thus, for modeling purposes, the wheat-producing parts of the globe have been subdivided into fine enough subunits to somewhat isolate and control regional differences in the mechanistic wheat growth variable that are not strongly correlated with or reflected by the mean temperature and precipitation variables.

The ranges of mean monthly temperatures and precipitation that have occurred in the U.S. spring wheat region are apparently sufficiently narrow (fig. 8-2) to obscure the nonlinear wheat-yield response curve hypothesized in figure 8-1(b). In fact, the existing U.S. spring wheat data do not justify an attempt to fit them to any model except a linear statistical model. Numerous other models were attempted with virtually no improvement in explained variance (table 8-I).

DATA SOURCES

Virtually all the U.S. spring wheat is grown in the states of Minnesota, Montana, North Dakota, and South Dakota. For these states, complete data are available on wheat production, area planted, area harvested, mean monthly temperatures, and mean monthly precipitation for crop districts (fig. 8-3) for the period from 1930 to 1971. The four states have been arbitrarily subdivided

by the U.S. Department of Agriculture into nine nearly equal districts by using county lines as the district borders. These data are published every year by each state office of the U.S. Department of Agriculture Statistical Reporting Service.

TECHNOLOGICAL INFLUENCES ON CROP YIELDS

The crop-yield data for the spring wheat region (fig. 8-4) illustrate the effects of the technological revolution in U.S. wheat production in recent decades. Thompson (ref. 8-5) claims that 1935 marked the beginning of this revolution, and he characterizes the effect of technology on wheat yields as a linear time trend that began with the 1945 data (ref. 8-6). Two problems must be confronted in any attempt to simplistically account for technological influences on crop yields. First, to what extent a time trend in crop yields actually reflects a trend in climatic variables must be discerned. Second, the slope of a linear approximation to the technological trend will depend greatly on the effectiveness of any decision that concerns the year in which the time trend should begin.

The time series of coefficients for the first eigenvectors of a matrix of mean temperatures and precipitation during June and July at each of the 22 crop districts for the period from 1931 to 1971 (fig. 8-5(a) and 8-5(b)) show no obvious time trend. However, the coefficients do suggest that the 1930's were generally hot and dry (which correspond to the Dust Bowl drought period) and that the 1940's were somewhat cooler and wetter than subsequent decades. Considering these observations and the variance pattern of very low wheat yields in the 1930's and considerably higher yields in the 1940's (fig. 8-4), the technological influence on wheat yields was approximated with a linear trend fitted by regression on the yields from 1952 to 1971. To test the effectiveness of this approximation, the time series of coefficients was examined for the first three eigenvectors of the matrix of wheat yields (corrected for the technological trend) in the 22 crop districts for the period from 1937 to 1971 (fig. 8-6(a), 8-6(b), and 8-6(c)). These coefficients show no obvious trend, which suggests that the technology correction was a reasonable approximation.

CROP-DISTRICT AGGREGATES

Wheat yields for all 22 crop districts were individually corrected for their technological trends and regressed against a variety of different combinations of temperatures and precipitation for various months of the spring wheat growth period (table 8-I). The linear multiple regression of wheat yields on the temperatures and precipitation, which were averaged over June and July for the historic record from 1940 to 1971, appeared to be the best simple model of those attempted. This model produced standard errors of the estimate that were very similar to those of Thompson (ref. 8-6) for multiple-regression models containing 18 independent variables and a virtually identical number of degrees of freedom. The 1930's were eliminated from the original

historic data set for these regressions because the severity of the Dust Bowl droughts apparently forced the wheat harvests to be exclusively from a relatively small percentage of the farmland that was seeded (fig. 8-7). Therefore, the data from the 1930's represented results from a different experiment compared to the remainder of the historic data set.

The resulting 22 regression models were then used to compute yields for the mean climatic variables for each of the 22 crop districts. These computed yields were subtracted from the mean yields for each crop district (corrected for technology), and the difference was expressed as a percentage of the actual mean yields. The percent deviations associated with each model were then considered as attributes of each model, which reflected the ability of the models to predict yields in each crop district. A Bray and Curtis ordination (ref. 8-7) was performed on the models, using these attributes as data, and the results of the ordination were used to aggregate crop districts on the basis of their similarities (fig. 8-8(a) and 8-8(b)). Five aggregates were established from the ordination (fig. 8-9).

SPRING WHEAT MODEL

The wheat productions and harvested farm areas for each crop-district aggregate were summed over the constituent crop districts, and the quotients of these sums provided weighted mean yields for the crop-district aggregates. These aggregate yields were then corrected for their technological trend in the manner previously described and regressed on the mean June-July temperatures and precipitation that were averaged across the constituent crop districts.

The spring wheat-yield regression equations for the northeast and north-central portions of Montana are

$$y = 11.2478 - 0.4118(T_{MJ}) + 0.0699(R_{MJ}) \qquad (8-1)$$

when $t < 1952$, $12.3 < T_{MJ} < 15.5°$ C, and $40 < R_{MJ} < 90$ millimeters, and

$$y = 11.2478 - 0.4118(T_{MJ}) + 0.0699(R_{MJ}) + 0.3078(t - 1952) \qquad (8-2)$$

when $t > 1952$, $12.3 < T_{MJ} < 15.5°$ C, and $40 < R_{MJ} < 90$ millimeters, where y is wheat yield in quintals per hectare, T_{MJ} is mean May-June temperatures, R_{MJ} is mean May-June precipitation, and t is year.

Spring wheat-yield regression equations for northwest, north-central, west-central, and central North Dakota are

$$y = 27.162 - 1.2816(T_{JJ}) + 0.0633(R_{JJ}) \tag{8-3}$$

when $t < 1952$, $16.6 < T_{JJ} < 20.0°$ C, and $30 < R_{JJ} < 110$ millimeters, and

$$y = 27.162 - 1.2816(T_{JJ}) + 0.0633(R_{JJ}) + 0.5817(t - 1952) \tag{8-4}$$

when $t > 1952$, $16.6 < T_{JJ} < 20.0°$ C, and $30 < R_{JJ} < 110$ millimeters, where T_{JJ} is mean June–July temperatures and R_{JJ} is mean June–July precipitation.

Spring wheat-yield regression equations for the Red River Valley, which includes northeast North Dakota and northwest and west-central Minnesota, are

$$y = 35.7511 - 1.3098(T_{JJ}) + 0.0120(R_{JJ}) \tag{8-5}$$

when $t < 1952$, $17.5 < T_{JJ} < 21.0°$ C, and $58 < R_{JJ} < 114$ millimeters, and

$$y = 35.7511 - 1.3098(T_{JJ}) + 0.0120(R_{JJ}) + 0.5760(t - 1952) \tag{8-6}$$

when $t > 1952$, $17.5 < T_{JJ} < 21.0°$ C, and $58 < R_{JJ} < 114$ millimeters.

Spring wheat-yield regression equations for southwest and south-central North Dakota and northwest and north-central South Dakota are

$$y = 30.4710 - 1.3824(T_{JJ}) + 0.0484(R_{JJ}) \tag{8-7}$$

when $t < 1952$, $17.2 < T_{JJ} < 21.3°$ C, and $44 < R_{JJ} < 102$ millimeters, and

$$y = 30.4710 - 1.3824(T_{JJ}) + 0.0484(R_{JJ}) + 0.5378(t - 1952) \tag{8-8}$$

when $t > 1952$, $17.2 < T_{JJ} < 21.3°$ C, and $44 < R_{JJ} < 102$ millimeters.

Spring wheat-yield regression equations for east-central and southeast North Dakota and northeast, central, east-central, and southeast South Dakota are

$$y = 38.5410 - 1.4637(T_{JJ}) - 0.0021(R_{JJ}) \qquad (8\text{-}9)$$

when $t < 1952$, $18.3 < T_{JJ} < 22.3°$ C, and $56 < R_{JJ} < 136$ millimeters, and

$$y = 38.5410 - 1.4637(T_{JJ}) - 0.0021(R_{JJ}) + 0.6221(t - 1952) \qquad (8\text{-}10)$$

when $t > 1952$, $18.3 < T_{JJ} < 22.3°$ C, and $56 < R_{JJ} < 136$ millimeters. The previous equations constitute a model of the U.S. spring wheat region that imitates the modeled historic data series with a mean deviation of only 11 percent (fig. 8-10).

CONCLUDING REMARKS

Each of the five crop-district aggregates established in this study is unique; some of the aggregate regression coefficients are over an order of magnitude different from others. The identification and use of these crop-district aggregates in the U.S. spring wheat model represents an improvement in large-scale crop-yield modeling.

Caution should be exercised in the use of statistical models such as the U.S. spring wheat model. The constraints placed on the model by restricting the independent variables to means of monthly temperatures and precipitation prevent the model from accounting for the mechanisms involved in wheat productivity. However, the possibility of building truly mechanistic models of domestic crop productivity for areas as large as the U.S. spring wheat belt is uncertain.

The most obvious attribute of the present model that deserves caution is the manner in which agrotechnological influences on crop yield have been modeled — that is, as a simple linear time trend. Technology has increased U.S. spring wheat yields by at least 9 ql/ha during the last 40 years (more than doubling yields); therefore, the absolute productivity could reasonably vary between a linear extrapolation of the time trend and a level representing no technology. For example, technological influences that are not modeled in the present climate/crop-yield model could very severely influence yields.

The U.S. spring wheat model concentrates exclusively on climatic influences on crop yields. However, as indicated in the section entitled "Model Form," the model only partially correlates with the mechanisms of climate/crop

interactions, and some of the variable climatic interactions with crops have been isolated to regions known as crop-district aggregates. Therefore, the model assumes a climatic uniqueness to each of these aggregates. For example, patterns of mean day-night temperature differences or the degree of cloudiness, which certainly must influence the functional form of plant productivity (fig. 8-1(b)), must remain relatively similar to those same factors exhibited in the near past within each crop-district aggregate. Therefore, if the character of climate (as differentiated from simple quantitative shifting of mean monthly climate variables) within each aggregate changes, then the model would probably lose some predictive capability.

Considering these modeling cautions, an attempt has been made to structure the climate/crop model simply enough to eventually extend the modeling effort by obtaining worldwide data and modeling wheat productivity. The U.S. spring wheat model was able to fit a 40-year data series with a mean error of only 11 percent and with virtually no errors in predicting annual yield trends.

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NEWMAN: I am not surprised that you say the trend of technology is difficult to discern because the crop-reporting data do not reflect that very clearly. Crop-breeding programs were inaugurated at various stages and reached maturity at various times. In the spring wheat belt, new and productive varieties began to appear approximately from 1952 to 1955. The crop-breeding program is one dimension. A second dimension is nitrogen fertilizer. If you consider these two items and if you discover when they arrived in the area and when they were absorbed into agronomic practice, you will find that these items are the dominant factors in causing this great trend in technology that we find so difficult to manage. These items vary across the country, depending on the region.

TRACY: I think I would agree that probably nitrogen fertilizer is dominating all other factors; however, acreage is being juggled, changing from one place to another over the past decade. We still have not settled on where wheat should be grown. Wheat is moving west, and corn is still encroaching on it from the east. We do not know how generalizable an in-depth study of technology in this country would be to the rest of the globe. If we cannot generate nitrogen fertilizer because of the power shortage or the energy crisis, then the best we can do is to give some type of range that shows what has been happening in technology and what might happen if we have no technology, which is a really gross range. Some persons tell me that we have peaked out on our technology. I do not know.

CHIN CHOY: You will find that Punjab, India, irrigates approximately 50 percent of the time. How is your model going to predict yield based on natural rainfall and temperature?

TRACY: I do not know what to do about disease or irrigation. Irrigation is probably somewhat easier to predict than disease. You can predict yield constantly, and a disease can occur and obliterate your prediction of a really good yield. We have not yet reconciled irrigation.

Model (a)	Standard error, ql/ha
$y = T_{JJ}^2 + R_{JJ}$	1.76
$y = T_{JJ} + R_{JJ}$	1.77
$y = T_{MJ}^2 + T_{JJ}^2 + R_{MJ} + R_{JJ}$	1.79
$y = 1/\ln(T_{JJ}) + R_{JJ}$	1.79
$y = T_{JJ}^2 + T_{JA}^2 + R_{JJ} + R_{JA}$	1.79
$y = T_{MJ}^2 + T_{JJ}^2 + T_{JA}^2 + R_{MJ} + R_{JJ} + R_{JA}$	1.80
$y = 1/\ln(T_{MJ}) + 1/\ln(T_{JJ}) + R_{MJ} + R_{JJ}$	1.80
$y = 1/\ln(T_{JJ}) + 1/\ln(T_{JA}) + R_{JJ} + R_{JA}$	1.81
$y = 1/\ln(T_{MJ}) + 1/\ln(T_{JJ}) + 1/\ln(T_{JA}) + R_{MJ} + R_{JJ} + R_{JA}$	1.82
$y = T_{JA}^2 + R_{JA}$	1.88
$y = T_{JJA} + R_{JJA}$	1.93
$y = T_{JJA}^2 + R_{JJA}$	1.93
$y = 1/\ln(T_{JAA}) + R_{JJA}$	1.94
$y = T_{MJJ} + R_{MJJ}$	1.96
$y = T_{MJJ}^2 + R_{MJJ}$	1.97
$y = 1/\ln(T_{MJJ}) + R_{MJJ}$	1.96
$y = T_{MJJA} + R_{MJJA}$	2.06
$y = T_{MJJA}^2 + R_{MJJA}$	2.07
$y = 1/\ln(T_{MJJA}) + R_{MJJA}$	2.08
$y = T_{MJ} + T_{JA} + R_{MJ} + R_{JA}$	2.08
$y = 1/\ln(T_{MJ}) + 1/\ln(T_{JA}) + R_{MJ} + R_{JA}$	2.08
$y = T_{MJ}^2 + T_{JA}^2 + R_{MJ} + R_{JA}$	2.09
$y = 1/\ln(T_{MJ}) + R_{MJ}$	2.18
$y = T_{MJ} + R_{MJ}$	2.19
$y = T_{MJ}^2 + R_{MJ}$	2.19
$y = 1/\ln(T_{JA}) + R_{JA}$	2.27

[a]T is mean temperature over subscripted months; R is mean precipitation;
MJ is May and June; JJ is June and July; JA is July and Aug.; MJJ is
May, June, and July; JJA is June, July, and Aug.; and MJJA is May, June,
July, and Aug.
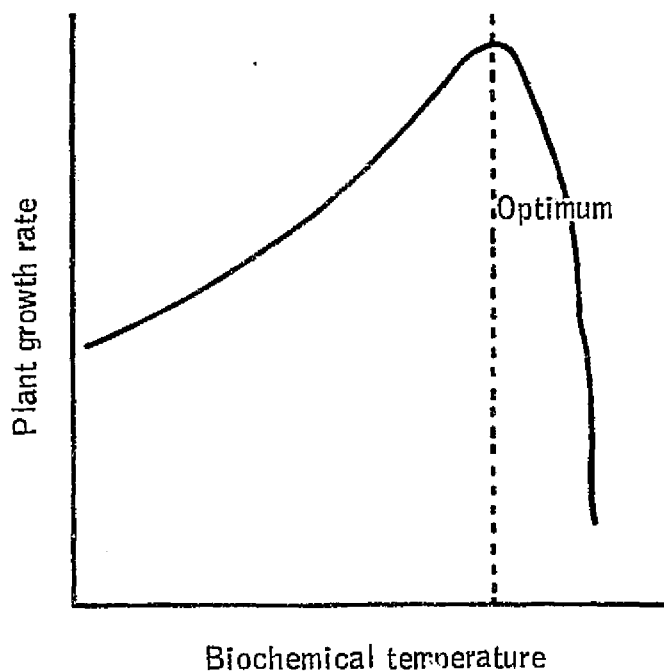
(a) Plant growth rates during well-watered laboratory conditions.
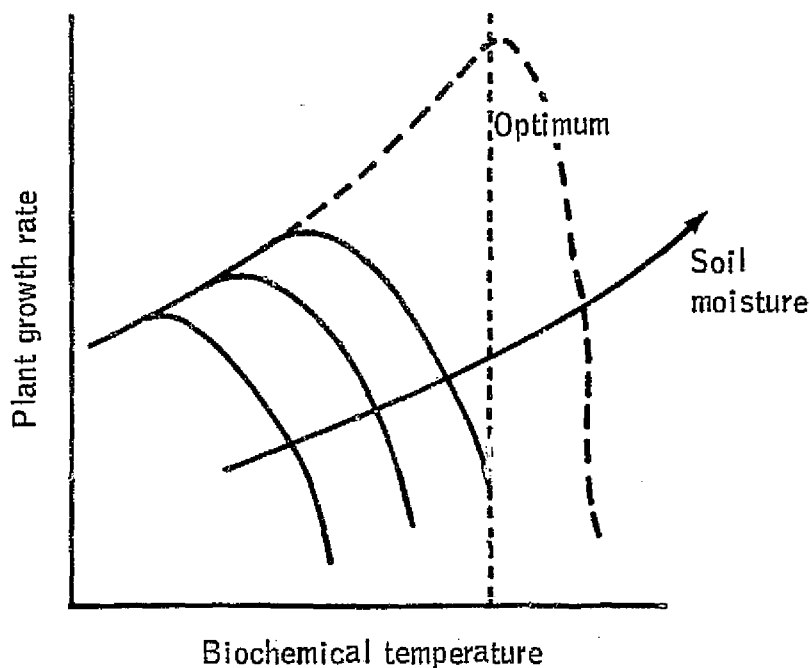
(b) Plant growth rates during conditions of inadequate water availability.

Figure 8-1.- Theoretical plant-growth-rate curves.

C-2
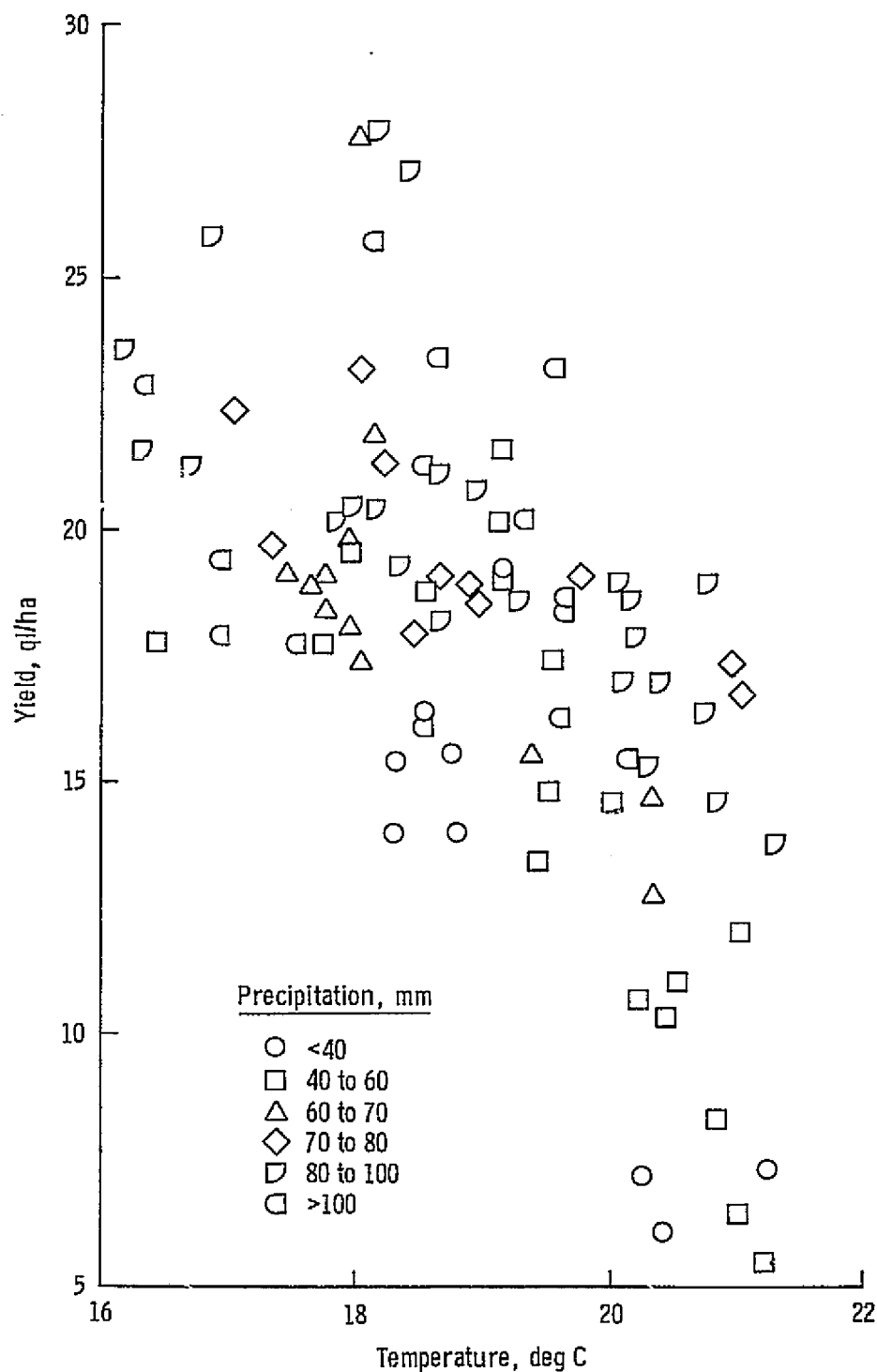
Figure 8-2.— Wheat yield as a function of June–July mean temperatures and precipitation for the seven crop districts of North Dakota, excluding the Red River Valley. The wheat yields were corrected for this technological trend beginning in 1952.
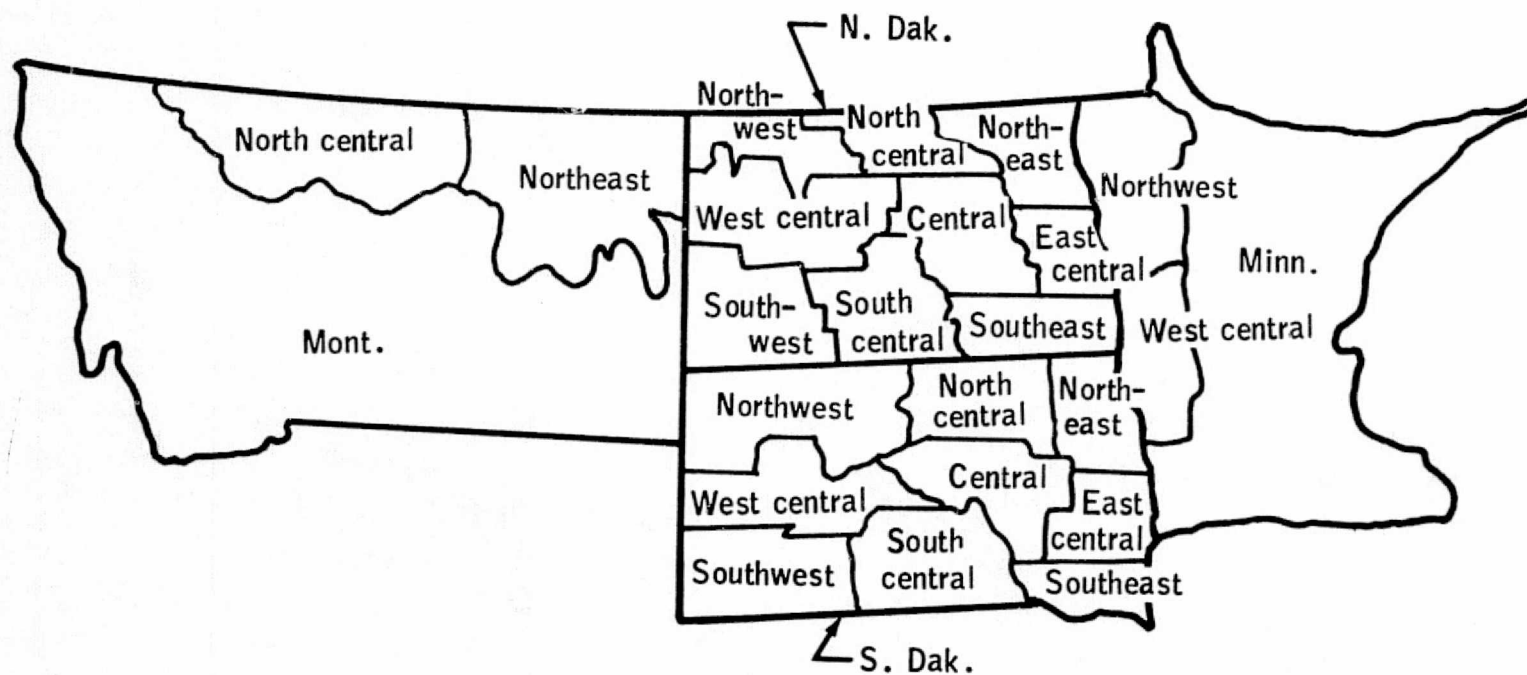
Figure 8-3.- Crop districts of the U.S. spring wheat region.
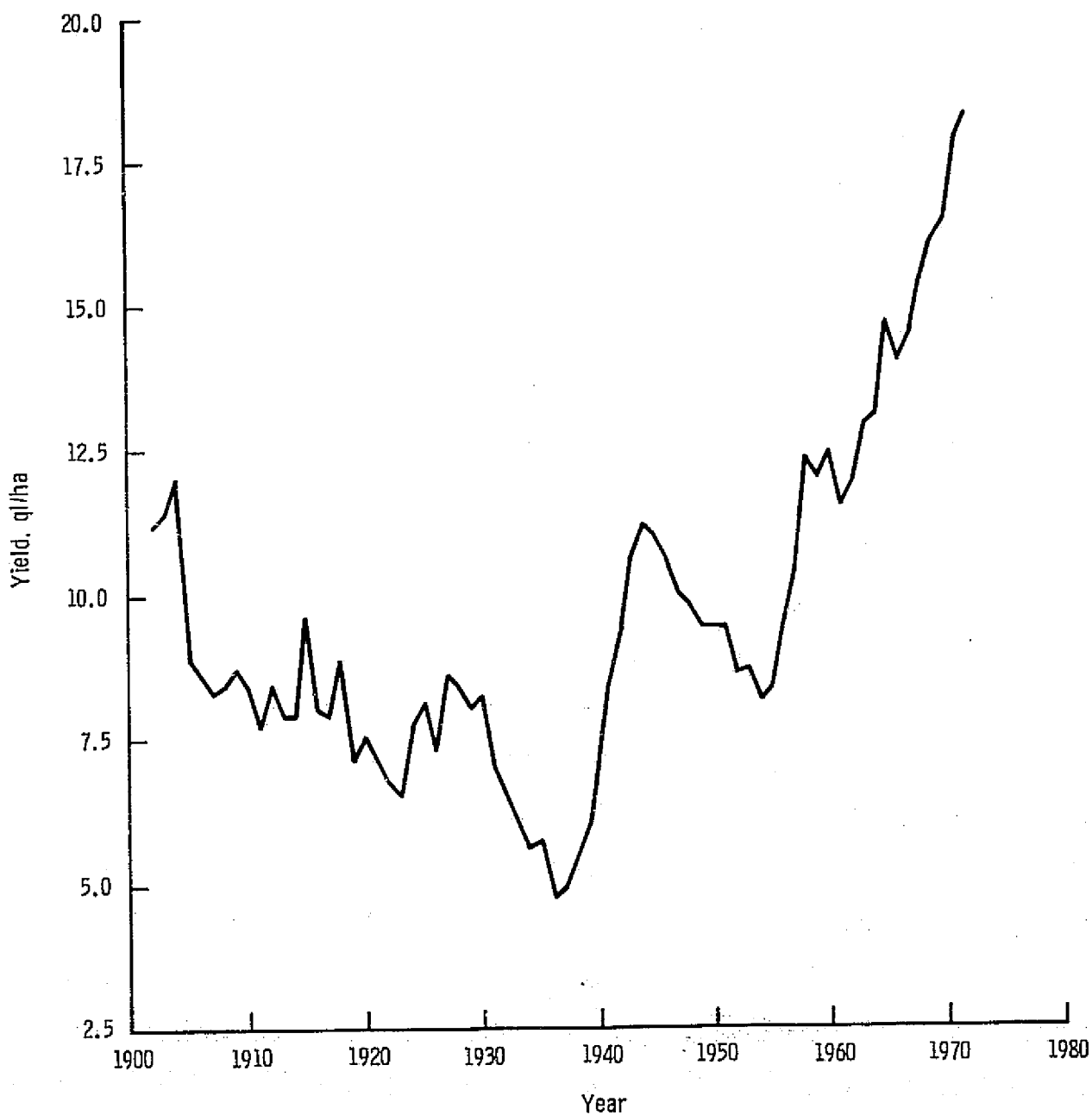
Figure 8-4.— Time trend of a 4-year running average of U.S. spring wheat yields.
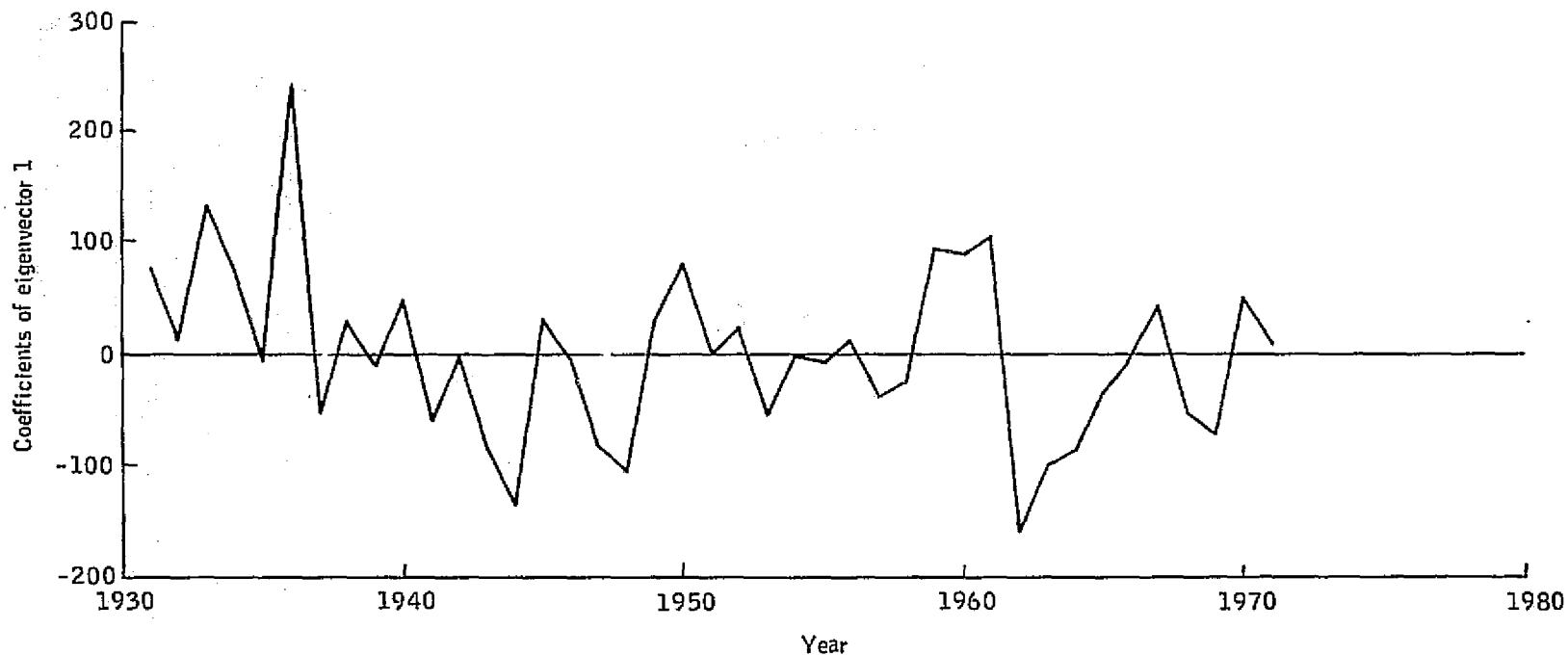
(a) Mean precipitation.

Figure 8-5.- Time series of the coefficients for the first eigenvectors of U.S. spring wheat yields.
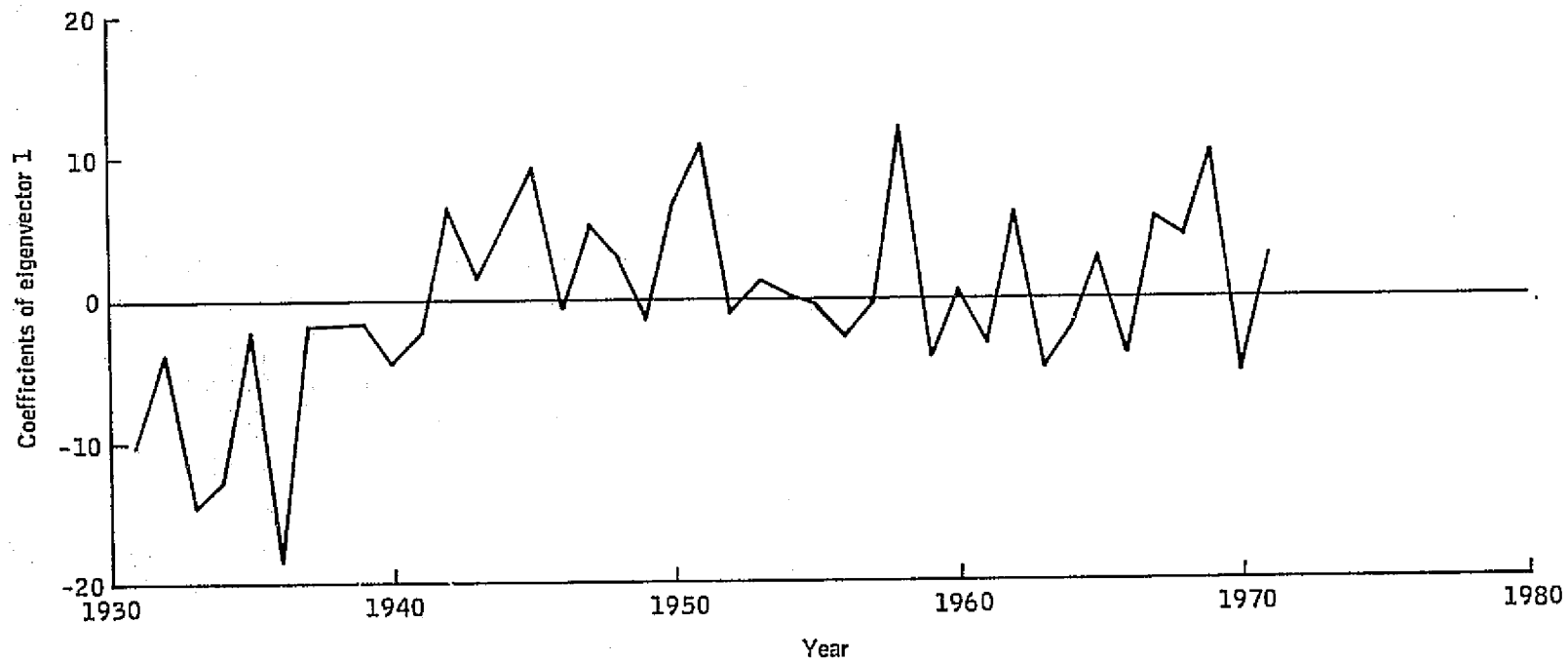
(b) Mean temperatures.

Figure 8-5.- Concluded.
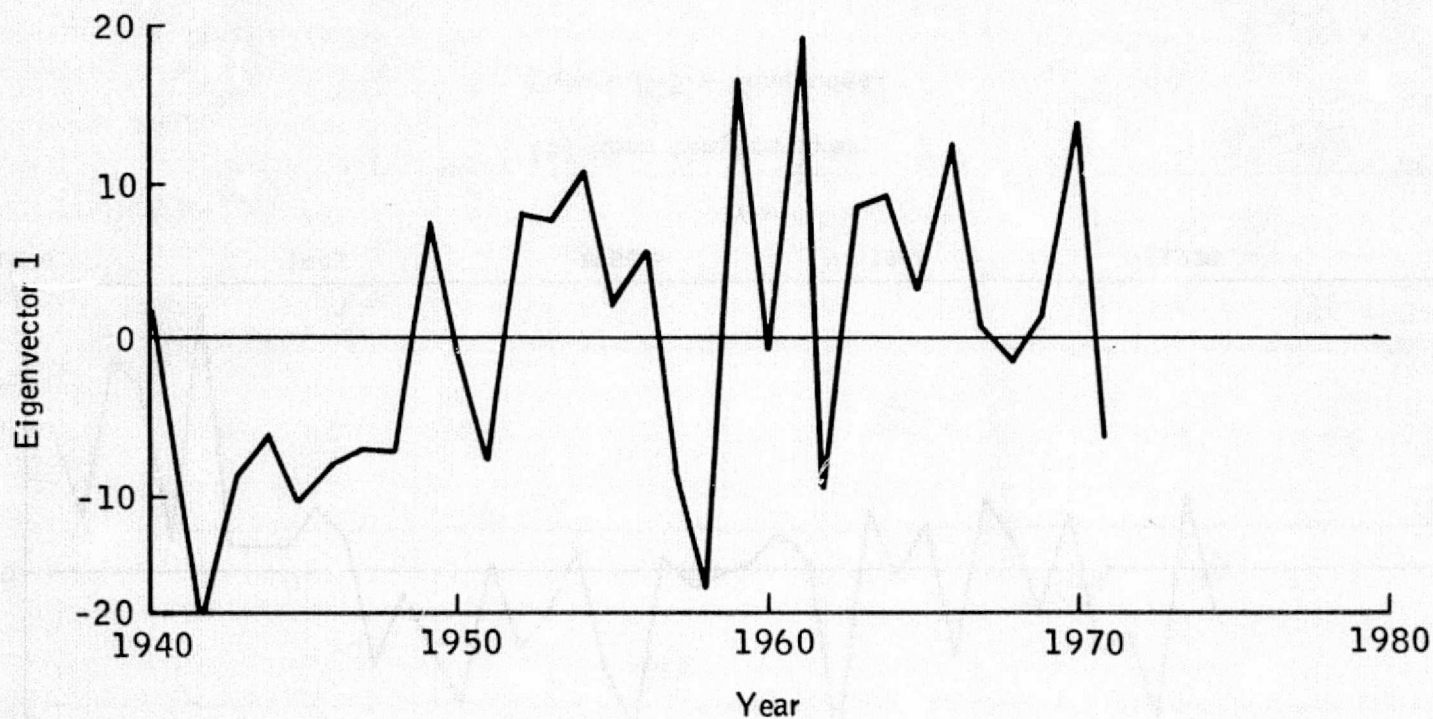
(a) Eigenvector 1.

Figure 8-6.- Time series of the coefficients for the first three eigenvectors
of a matrix of the 22 crop districts. The wheat yields were corrected for
their technological trend.
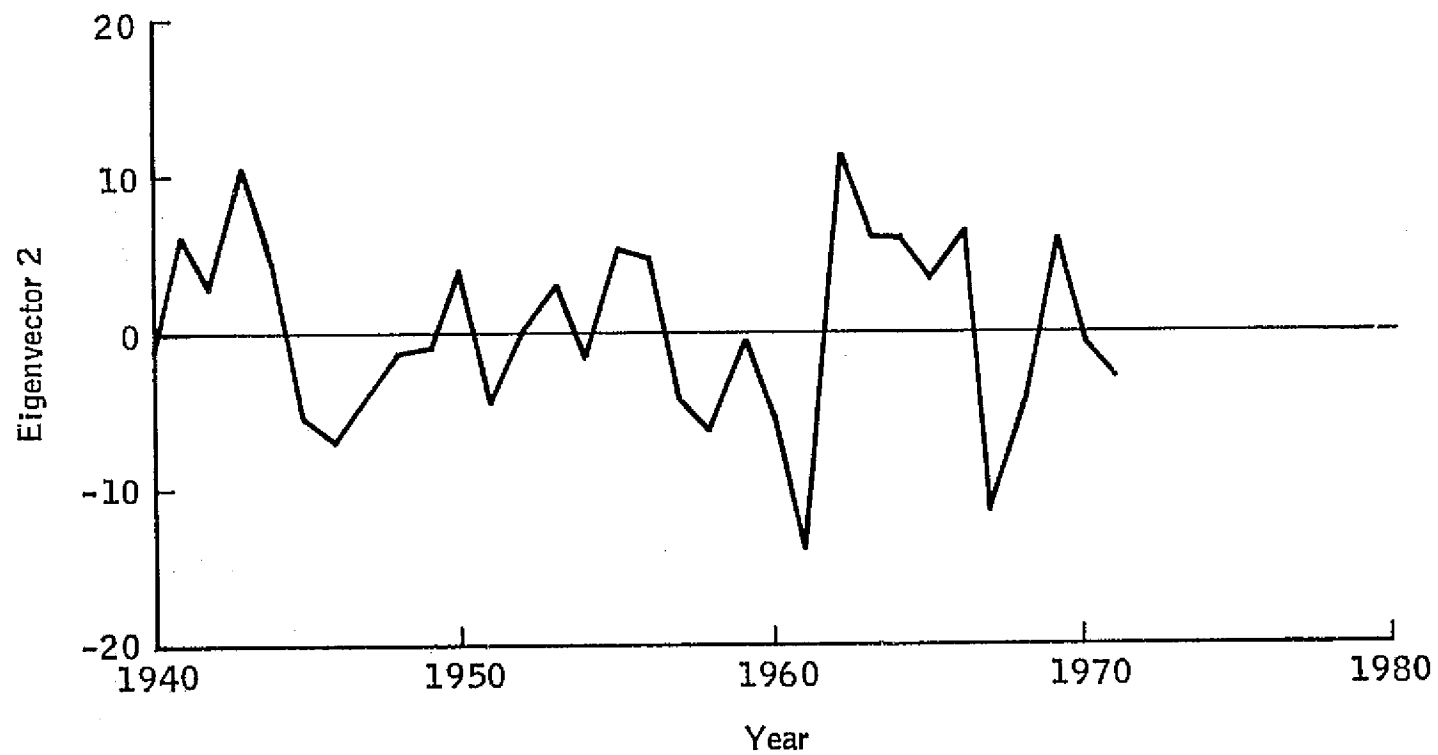
(b) Eigenvector 2.

Figure 8-6.- Continued.
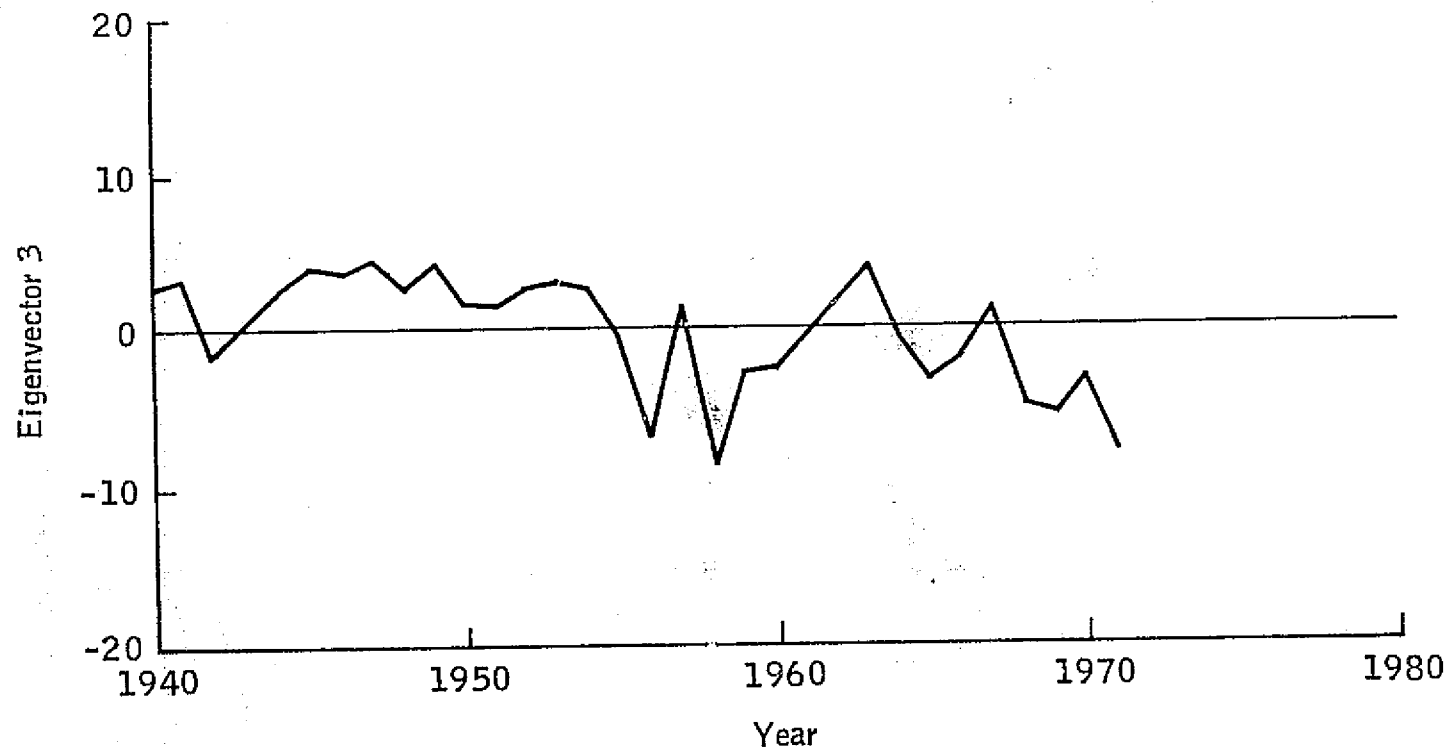
(c) Eigenvector 3.

Figure 8-6.- Concluded.
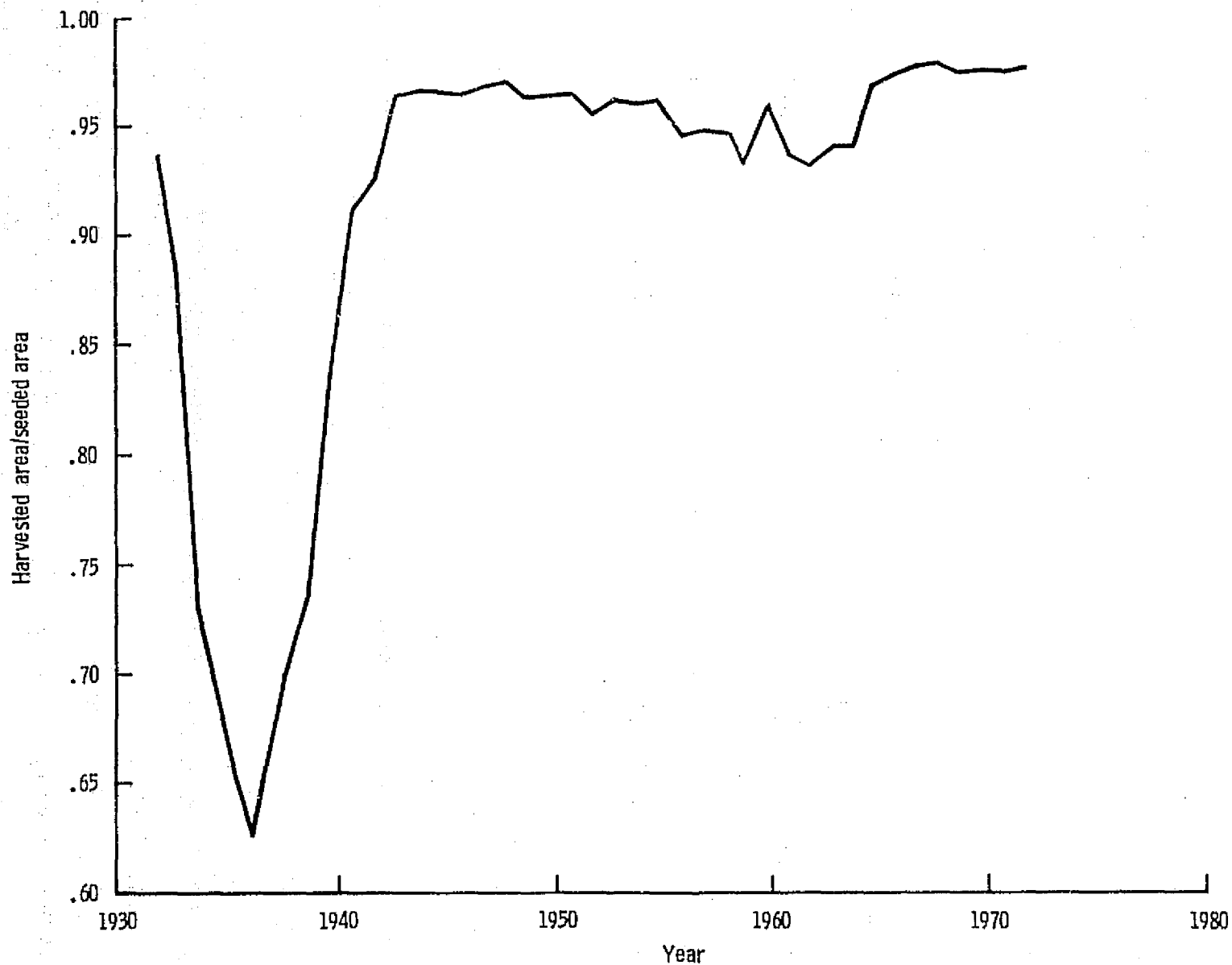
Figure 8-7.— Ratio of harvested area to seeded area as a function of time for a 4-year running average of the U.S. spring wheat region.
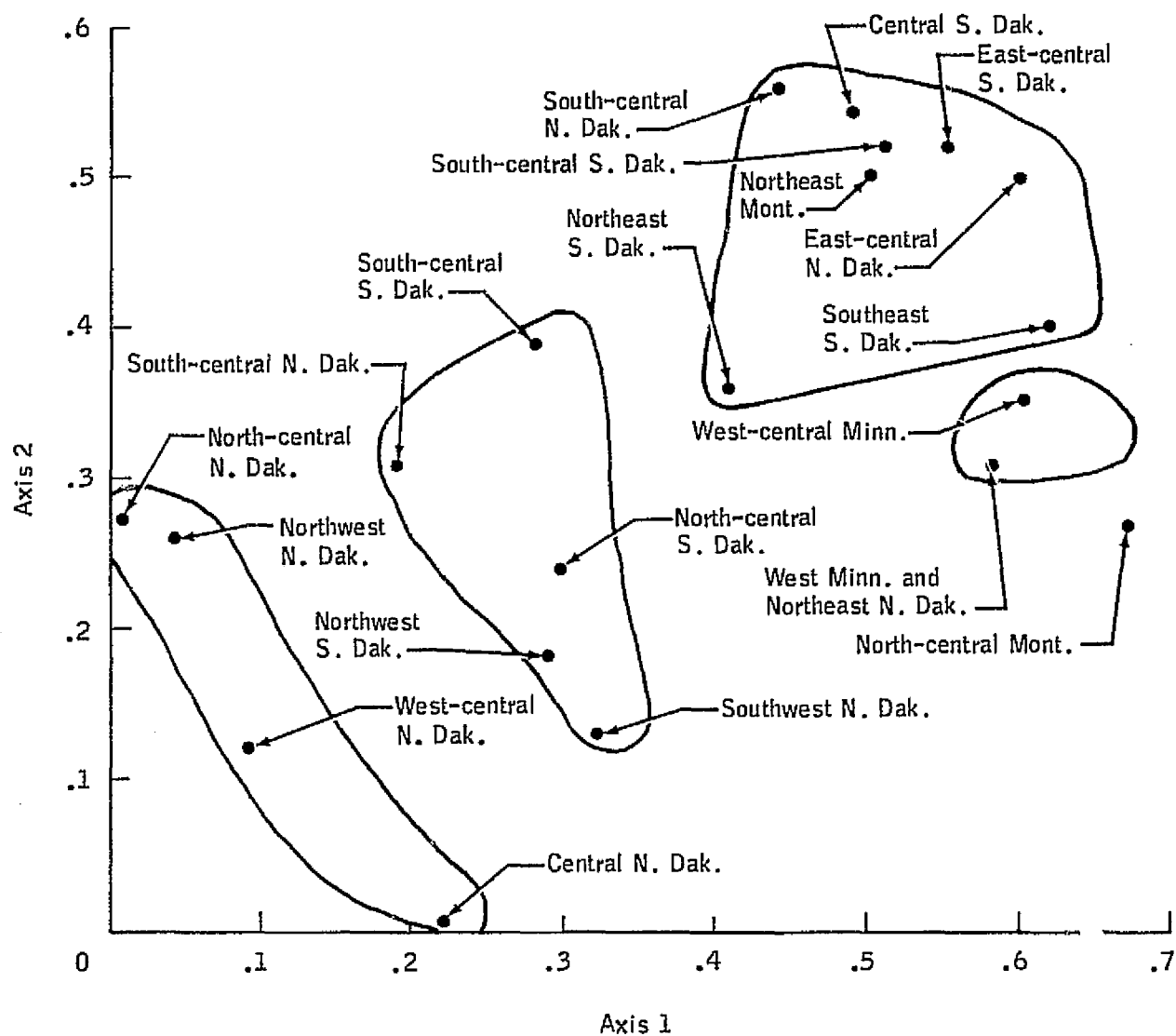
(a) Axes 1 and 2.

Figure 8-8.— A Bray and Curtis ordination of spring wheat regression models of individual crop-district yields (ref. 8-7).
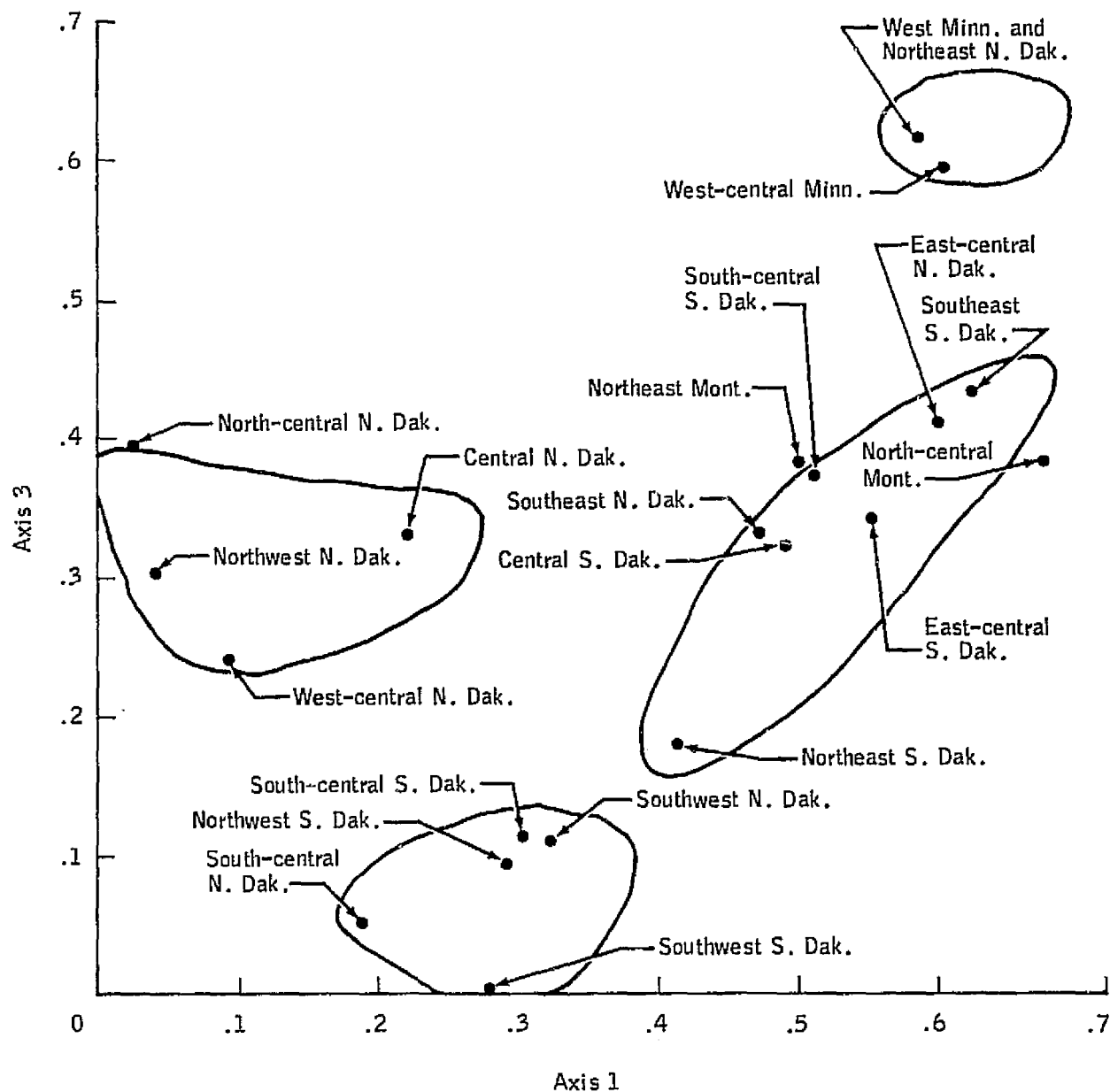
(b) Axes 1 and 3.

Figure 8-8.- Concluded.
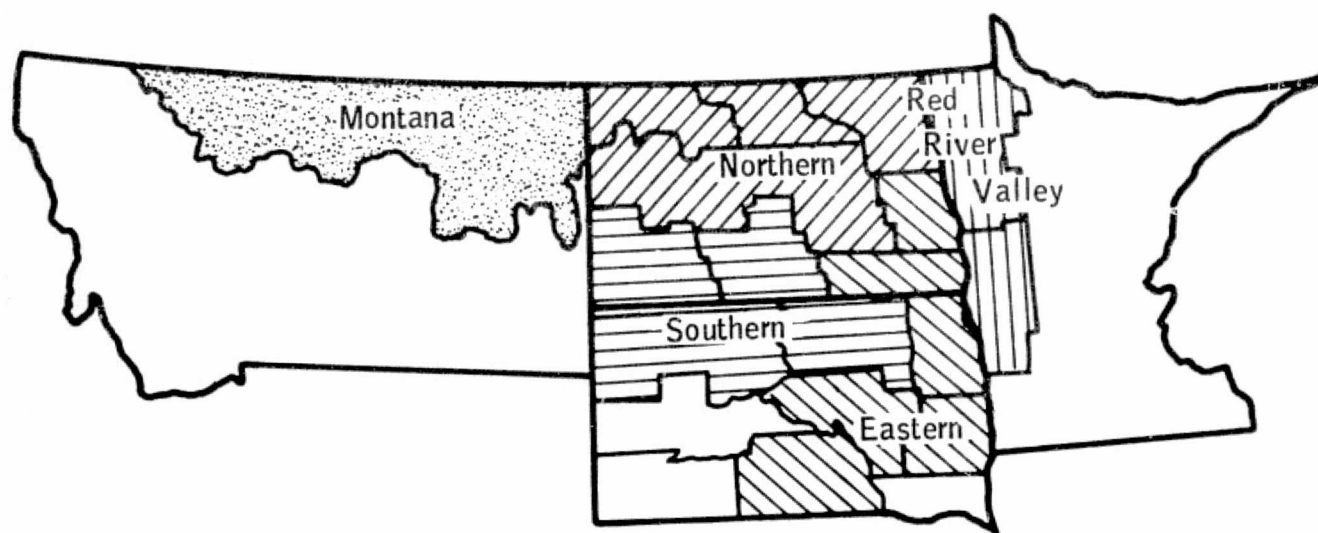
Figure 8-9.- Crop-district aggregates for the U.S. spring wheat region.
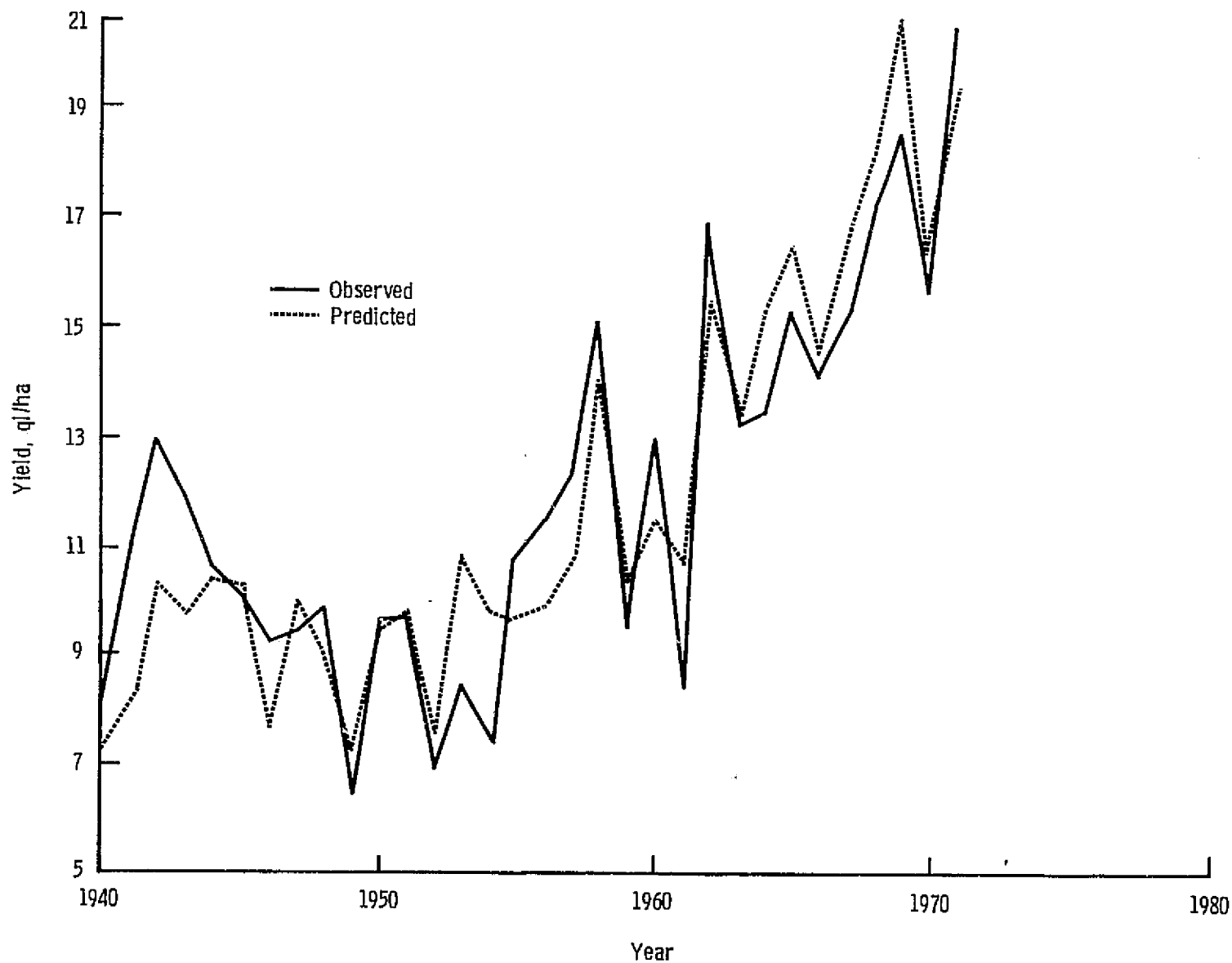
Figure 8-10.— Observed and model-predicted wheat yields for the U.S.
spring wheat region.

9. WHEAT-YIELD ESTIMATES BASED ON WEATHER:

RESEARCH AND APPLICATIONS IN CANADA

By George W. Robertson*

The need for crop weather prediction in Canada occurred early in 1962 after a very serious drought in 1961 and after the Minister of Agriculture announced large sales of wheat to the People's Republic of China. After selling the wheat, indications were that a probable insufficiency would exist at harvesttime. The problem was to indicate early in May what the prospects were for the total production at harvesttime. Furthermore, an updated estimate was required weekly.

The preparation of these estimates became the responsibility of the Agrometeorology Section of the Research Branch of the Canadian Department of Agriculture. Early research that had been undertaken by Staple and Lehane in Swift Current, Saskatchewan (refs. 9-1 and 9-2) offered an approach. Using their models, regression equations were developed for 30 crop districts in the Canadian Great Plains.

The model that was developed involved only monthly precipitation data and wheat acreage. Precipitation data from 65 stations were used. These data were weighted according to the wheat acreage in the vicinity. A quadratic term was used to help explain the decreasing response of yield to higher rainfall amounts, particularly in the more humid area of Manitoba.

After determining specific regression coefficients for the 30 crop districts, many districts were discovered to be similar; thus, they could be grouped into 8 major soil-climate zones. The soil variability factor was accounted for by the different regression coefficients for each zone. The estimates were updated weekly by concurrently using observations made up to estimation time (Monday morning) and climatic data for the remaining period up to harvesttime. The technique is fully described by Williams and Robertson (ref. 9-3).

In the drought year 1961, average wheat yield on the Canadian Great Plains was only 10.6 bu/acre, and total production was 260 million bushels. Estimates of total production in 1962 at the end of May, June, and July were 532, 515, and 540 million bushels, respectively. The total production was reported to be 546 million bushels. In 1963, similar estimates at the end of each of the 3 months were 558, 597, and 652 million bushels, respectively. The total

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*Canadian Wheat Board, Winnipeg, Manitoba.

production was reported to be 698 million bushels. Even as early as May, the estimates reflected the final production. At the end of June 1962, a potential reduction in yield was indicated because of low rainfall in June. However, this calculated reduction was not nearly as great as crop observers had indicated. July rains saved the crop, and by the end of July, the estimate of 540 million bushels was exceptionally close to the actual total of 546 million bushels. One advantage of the system is that it objectively integrates weather data for a large area and produces an indication that is less irrational than casual observations by experts. In 1963, the crop year began favorably, and conditions remained better than average throughout the growing season. The estimates of production at the end of each of the 3 months showed a definite increase over the growing season. The final production estimate of 652 million bushels was close to the total production of 698 million bushels.

These weather-based estimates and trends proved valuable to marketing agencies. The estimates provided confidence that a specific wheat crop was expected, and they also provided considerable leadtime for decisionmaking. The first official production forecast made by actual observation was available early in September, and the first official estimate of production was released about mid-November. The 1963 bumper crop provided Canada with a wheat surplus; thus, no further weather-based estimates were undertaken until recently.

During the intervening 10 years, the Agrometeorology Section undertook much research on models and submodels. Williams (refs. 9-4, 9-5, and 9-6) improved his basic model by introducing a term for potential evapotranspiration. During this research, weather data were found to be related to wheat growth at certain specific developmental periods. Because the prairie wheat crop is not at the same stage of development at one time over the entire region and because this developmental stage varies from year to year, a biological time scale rather than a calendar time scale should be used. This requirement was responsible for the development of a biometeorological time scale for wheat based on photoperiod and day/night temperatures (refs. 9-7 and 9-8).

Wheat was found to respond more to soil moisture than to the amount of precipitation. If extensive soil moisture observations did not exist, soil water was estimated from existing climatological data. The early work of Holmes and Robertson (ref. 9-9) that resulted in the modulated soil moisture budget was expanded, and the verstile soil moisture budget was developed (ref. 9-10). This budget enables the daily calculation of soil moisture by layers with an accuracy almost equal to that of taking soil samples. This model requires daily precipitation and daily maximum and minimum temperatures as input data.

Other related research was undertaken to learn more about the factors that affect yield and the critical period when these factors are important (refs. 9-11 and 9-12). Of particular concern was the development of a model that would incorporate various weather factors in much the same manner as does the crop. Some reluctance existed in accepting the following simple regression equation.

$$Y = a_0 + a_1X_1 + a_2X_2 + \ldots \tag{9-1}$$

Although this type equation provides a relationship between yield and several weather elements, it does not provide useful and reproducible knowledge regarding the characteristic response of wheat to individual elements. For example, to add temperature to rainfall or to compensate a zero temperature by adding in more rainfall to estimate yield is not logical. To add functions of certain weather elements seems more reasonable physically and physiologically — for example, rainfall and evaporation to obtain a water balance. To multiply functions of other elements to provide modifications is also more reasonable — for example, temperature and solar radiation should modify the influence of soil water or the water balance. This rationale was responsible for the development of a factorial-type regression equation of the general form

$$Y = \left(a_0 + a_1X_1 + a_2X_1^2\right)\left(b_0 + b_1X_2 + b_2X_2^2\right) \ldots \tag{9-2}$$

This type relationship was used for the biometeorological time-scale calculations (refs. 9-7 and 9-8) and for estimating yield (ref. 9-13). A factorial yield/weather model that incorporated an antecedent crop-condition term was developed by Robertson. These models provide realistic yield estimates, and the nonlinear response functions for individual weather elements appear to agree well with experimental results obtained under controlled conditions. Such relationships are more universally applicable for yield estimates than the simpler linear-type regression equations.

The year 1972 was a turning point in worldwide food supply and demand. Heat and drought in the U.S.S.R. and floods and droughts in other parts of the world reduced food production at a time when affluence and population growth caused demand to overtake supply. As a result of these factors, surplus stocks of grain in Canada, the United States, and other major exporting nations fell to an alltime low, which resulted in a threefold to fourfold increase in grain prices.

Because of the grain-stock shortage and high prices, grave concern was evidenced by exporting nations regarding the pricing and allocation of grain among importers. To assist with decisions early in the crop year of 1973, the Canadian Wheat Board asked for weather-based wheat-yield estimates on a weekly basis (as had been done in 1962 and 1963). Former models and programs were reactivated with some improvements, and models were developed to estimate oats and barley yield. The request for service came too late to incorporate all the submodels that had been developed in the intervening 10 years. The real-time estimate of the expected wheat supply was relatively simple.

The real-time estimate of wheat demand was a more difficult problem.
Because real-time estimates of demand (based on crop conditions) in other
countries were required, data from the 6-hour synoptic reports of the World
Weather Watch Program were useful. These reports are transmitted rapidly and
are usually available from most parts of the Northern Hemisphere within 1 to
2 hours after the observations are taken. These observations are available
from the Canadian Meteorological Center in Montreal. Once weekly, the Canadian
Wheat Board obtained copies of the reports on magnetic tapes. Only minor
problems were encountered in obtaining and reading data from the tapes. The
major problems were that stations did not report regularly and that the nec-
essary information (precipitation and temperature extremes) was frequently
missing. Research is continuing on the use of synoptic data for estimating
crop conditions. These reports contain much useful information. The greatest
weakness is the lack of reliable reports on rainfall data, which are necessary
in preparing yield estimates.

As supply and demand of food become tighter, a greater emphasis will be
placed on the real-time monitoring of potential sinks and sources of food.
Because weather is the most important factor controlling the variability in
food supply and demand, food distributors will depend on weather information
as an indication of supply and demand. Because of the vast global weather-
observing programs and the telecommunications systems, the World Weather Watch
Program is a logical source of real-time information for this global crop
weather service. Considerable developmental research will be required to adapt
the factorial yield/weather model (or improved versions of it) to crops other
than wheat. The food crisis in Canada is creating an increasing interest in
this area of research and service. The need for a worldwide weather and crop-
condition surveillance will eventually be realized as a necessity.

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QUESTIONS AND ANSWERS

NICHOLS: I have examined this particular product model you discussed. An
             error in one of the input parameters probably would be multiplied
             through the model. Have you done any sensitivity analysis in this
             model concerning errors in the estimate or, in some cases, the
             guesstimates of the inputs?

ROBERTSON: I do not think that we have subjected this model to all the tests
             to which it should be subjected. We tried to break yield into its
             components: grain weight, number of grains per head, and number of
             heads. We tried to multiply these three components, which seemed
             very logical because these three components are established in the
             plant at different times in the life of the plant. For example,
             the number of spikelets on a head is established at the time of
             jointing. Temperature and rainfall at the time of jointing deter-
             mine the number of kernels, the number of heads, and the number of
             spikelets per head. We did get a multiplication of sensitivity,
             which produced ridiculously high or low values. In other words, we
             could predict yield much better than we could predict yield
             components and multiply the components to get the final answer. I
             did put some restraints on the solution to obtain the coefficients;
             thus, these restraints may have reduced the sensitivity somewhat.

HARTLEY: Are these data that you are using available from experimental
             stations, or are they from your gages? You do not have records of
             the yield Y for consecutive periods. You only have the final
             yield, but you can determine analytically what the form of the final
             yield is, if you are solving this mathematically. You can pick the
             coefficients a_0, a_1, a_2, and the other ones in the other

             parentheses by having only the final Y value. Is this assumption
             correct?

ROBERTSON: Yes. We relate the final yield that we have to the antecedent
             rainfall, which is preseason rainfall, because that rainfall is
             stored in the soil and available to the plant. In regression
             terminology, this preseason rainfall accounts for 26 percent of
             the variability of the yield in this particular example. As we
             continue throughout the period, we add in another month of weather;
             we add in the rainfall, the temperature, and so forth. Then we can
             account for generally as much as 35 percent of the variability. In
             the particular example that I took for Swift Current, we can
             account for 73 percent of the variability.

10. A PROPOSED TECHNIQUE FOR ADJUSTMENT OF

YIELD PREDICTION FOR FERTILIZER USE

By H. O. Hartley[*]

The objective of the proposed model is to predict yield per acre on a real-time basis. Even if certain predictors appear to be very important from a scientific and theoretical viewpoint, retaining them is useless if they were not made on a real-time basis. Real-time basis means that predictions are needed before harvest — that is, before the end of the growing season. A prediction model must be adjusted for the amount of fertilizer application. In 1974, a reduction in yield is expected because of a fertilizer shortage. Thus, the proposed model must be able to include the latest information on fertilizer application rates in conjunction with the environmental prediction law.

The proposed technique to improve yield models is based on meteorological predictors by incorporating adjustments that use information on the application of commercial fertilizers. Even with the incorporation of these adjustments, numerous factors, which have not been incorporated into the model, affect wheat yield. Some of these factors affecting yield are soil content of plant nutrients, varietal differences, and cultivation practices other than irrigation and fertilization. Irrigation has been noted by developing separate models for irrigated and nonirrigated wheat.

Theoretical consideration of plant growth curves can establish that the combined effects of meteorological variables w and fertilizer application rates x on the yield per acre y can be represented (apart from a statistical error) as the following product model.[1]

$$y = g(w) \cdot f(x) \tag{10-1}$$

where the vector w represents such variables as soil moisture content at seeding, temperature at seeding, and available moisture during various stages of plant growth; the vector x represents fertilizer application rates at or after seeding of nitrogen (N), phosphorus (P), and potassium (K); and g(w)

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[*]Texas A. & M. University, College Station, Texas.

[1]It is intended to validate the product model (eq. (10-1)) by using experimental data from agricultural experiment stations conducting wheat–fertilizer experiments on the same site in different years under varying meteorological conditions.

and $f(x)$ are multivariate functions. The vector w does not represent straight meteorological variables because too many variables would enter into this function. Relevant indices have been chosen instead. The types of indices include length and intensity of drought periods that have been computed from precipitation and temperature data by using empirically verified formulas for evaporation. Thus, many meteorological data will be converted into indices. The mathematical forms of $f(x)$ that have been used in the literature on agricultural production functions are characteristically laws that are quadratic in N, P, and K, rates of application per acre, or quadratic in $\sqrt{N}$, $\sqrt{P}$, and $\sqrt{K}$ functions. Very little difference is achieved by switching the law.

To partially account for the effects of soil types and cultivation practices and their interactions with w and x, a law of this type (eq. (10-1)) will be estimated for each of many strata within the wheat-growing regions. These strata will approximately correspond to the U.S. Department of Agriculture (USDA) crop-reporting districts. Both climatic and soil-type strata will be used. Hopefully, these conditions will be roughly uniform within a stratum. Therefore, the approach is not global. To develop custom-made laws for an individual stratum is preferable because of the benefit of larger totals obtained by aggregating the predictions from each stratum. Moreover, changes in the varieties planted and the cultivation practices will be accounted for by a technological time trend.

Essentially, two data banks will be used to build the model. One data bank is available from the USDA and the National Climatic Center (NCC). The second data bank will be fertilizer experiments conducted by agricultural experiment stations to relate response surfaces. Unfortunately, extensive data banks that provide both environmental details and fertilizer application rates are not available.

A county will be used as the unit of the data bank for environmental studies. The source for the yield per acre y will be the USDA county estimates of reported yields obtained by the Statistical Reporting Service (SRS) over the last 6 to 8 years. Reported yields are obtained by vast survey activities of the SRS. One activity is to have the farmer report by mail his yield per acre after harvest. The SRS then compares these reported yields with yields obtained by direct measurements. The associated meteorological predictor values w will be computed from the official precipitation and temperature records of all stations in the county and will be available from the NCC. Because no associated county records of fertilizer application rates x are available, the simultaneous evaluation of both $g(w)$ and $f(x)$ in equation (10-1) is impossible and necessitates the formal definition of u_{it} is equal to $\log y_{it}$ is equal to log yield for county i in year t; w_{it} is equal to the meteorological vector for county i in year t; and x_{it} is equal to the fertilizer vector for county i in year t. From equation (10-1)

$$u_{it} = G\left(w_{it}\right) + \log f\left(x_{it}\right) + \varepsilon_{it} \tag{10-2}$$

where $G(w_{it})$ is equal to $\log g(w_{it})$ and ε_{it} is a statistical error, which results from a sampling error. Because the predictor values x_{it} are not available, equation (10-2) should be written as

$$u_{it} = G\left(w_{it}\right) + Av\left[\log f\left(x_{it}\right)\right] + e_{it} \tag{10-3}$$

where $AV\left[\log f\left(x_{it}\right)\right]$ is the average over all counties in the stratum and will be a function of the year t only and where ε_{it} incorporates the error ε_{it} plus the deviation $\log f(x_{it}) - Av \log f(x_{it})$. Official USDA statistics note that, in past years, the fertilizer application rates as a function of time in a given stratum can be represented as a linear or, possibly, a quadratic time trend. Thus, equation (10-3) may be written as

$$u_{it} = G\left(w_{it}\right) + \alpha + \beta t + \varepsilon_{it} \tag{10-4}$$

where the mathematical form of $G(w_{it})$ will require evolution by data analysis, and α and β are constants of the equation.

If the product form (eq. (10-1)) of the model is accepted, the fertilizer response surface can be estimated from isolated experimental data from N, P, and K experiments conducted in the stratum during any year. Such experimental data may not be available for all relevant strata. The N, P, and K surface fitted to the experimental data is denoted by $F(x)$; the function $f(x)$ then can be estimated by

$$f(x) = F(x)\exp\left[-G\left(w_{it}\right)\right] \tag{10-5}$$

where w_{it} refers to the meteorological vector of county i in the year t of the experiment.

Because the Y_{it} values are the final reported figures for yield per acre from the SRS county estimates, they will not be available for predictions of yield per acre early in the growing season. This lack of values is the main reason for developing the yield model (eq. (10-1)). A comparatively minor time lag occurs in obtaining the w_{it} from the NCC — that is, a delay of approximately 2 weeks after the month to which the record applies. However,

considerable difficulties arise with the evaluation of $f(x_{it})$ for the current year t. Presently, the following estimators are being contemplated.

Because the average effect of fertilizer application $f(x)$ in the current year t has already been estimated by $\exp(\alpha + \beta t)$, the estimate of an adjustment to this value is required for the stratum yield per acre caused by a departure of the actual fertilizer application from the extrapolated value of the time-trend function $\exp(\alpha + \beta t)$. Accordingly, the stratum ratio of $f(x)/\exp(\alpha + \beta t)$ is estimated by

$$f(x)/\exp(\alpha + \beta t) = pf(0)/\exp(\alpha + \beta t) + qR \qquad (10\text{-}6)$$

where p is the proportion of wheatfields not receiving any fertilizers (estimated from the USDA SRS crop-production releases), q is equal to $1 - p$, and the value of the ratio R is given by

$$R = \frac{f(\zeta \hat{x})}{F(\hat{x})} \qquad (10\text{-}7)$$

where $\hat{x}$ is the extrapolated rate of fertilizer application to all wheatfields in the state (obtained from the USDA SRS crop-production releases), and ζ is an estimate of the shortage or excess of fertilizer application for the current season (computed from the USDA SRS commercial fertilizer releases).

CHIN CHOY: I used essentially the same model as Dr. Hartley's model. We had
$\hat{y}$ as expected growth, which is ultimately related to wheat yield,
is equal to some constant, which we obtained from the regression
line. That constant is the function of mean daily temperature
plus the water content of the soil plus the expected previous
growth. We were planning to put in a fertility value of this form,
where F is fertility of the soil. We did this for forage, and we
looked at our error. The error term bounced, which meant it was
random. We were looking at a three-county area. We had to deduce
one of two things. One, a random error existed, or two, something
was not built into this model that should be there. We could not
accept the random error term because that year it was approximately
22 percent. Thus, we had to break the state down into what the
Soil Conservation Service classified as class 1, class 2, class 3,
and class 4 soils. The model fit without the fertility portion
for class 1 and 2 soils — in other words, soils that were not
seriously eroded. For class 3 and 4 soils, which were seriously
eroded, the model did not fit. This problem goes back to this fer-
tility value. No data bank is available that takes the N, P, and
K values of the soil throughout the growing season. Nitrogen is
not very important, but phosphorus surely is. I think what happened
was that in class 3 and 4 soils, the phosphorus that was applied
was washed off; thus, the plants did not receive any phosphorus.
However, the plants probably did receive nitrogen. If Dr. Hartley
is going to average over the entire state, this effect may be
averaged out. I do not know. I am extremely curious to see what
kind of result he obtains.

HARTLEY: First of all, I do not think your form is identical with the
product form that I described. If I understood you correctly, this
is y_i and this is y_{i-1}. This period is from i-1 to i,
correct?

CHIN CHOY: The i refers to the day; i-1 is the cumulative growth up to
that date.

HARTLEY: Okay. No y existed in my product law on the right side. What
you have here is a different equation or a law that will generate
the mathematical form of y. What will the law be? It will be
exponential if these factors were constant over i. The fertilizer
rate presumably is a constant over the period i. If you have
variables that vary over i, you do not get the exponential law.
You are committed to a particular form of the law that is generated
by this equation, which would be the exponential law, if these
factors were constant. We left the law completely open, and we
were only concerned with the final value of y. However, the
point that you raised that the final yield is a product of

environmental variables multiplied by a function of the fertilizer rates is very well taken. We expect exceptions to this rule. For example, in arid regions, high rates of fertilizer are not applied because it can be detrimental during a very dry season. This example would be a departure from the product law. However, we are allowing a different product law for each stratum, and we are only averaging counties within a particular stratum. Thus, we are looking at a fairly homogenous set. Variations may exist within a stratum of soil type and climatological conditions, and they may cause departures from the product law. To monitor the product law, we are hoping to take data from experiment stations at which we are operating on the same soil type year after year, conducting experiments in different years, and having weather conditions change from year to year. If you are fitting a response surface every year, you can see whether the response surfaces obtained year after year follow the product law.

BARGER: This correction factor for fertilizer rate could be negative. If the environmental expectation is low, then your function of the fertilizer application might be negative rather than positive. From your experimental data, this result would be possible.

HARTLEY: Yes, you are right because we have estimated that $f(x)$ from actual response data. If our environmental function is not very good, then this division by that $g(w)$ in the actual fertilizer experiment might overcorrect or undercorrect, depending on how well the environmental function has already been estimated. Errors in the environmental response function may then reflect themselves in having too low an $f(x)$ or too high an $f(x)$.

BARGER: I was referring to the errors as much as the level of the environmental expectation. If the interaction is low, then the fertilizer effect might actually be negative, as you suggest.

HARTLEY: Do you mean the interaction between the environmental factors?

BARGER: The effect of the fertilizer will be positive if rain is plentiful and negative if rain is not plentiful.

HARTLEY: Yes, the negative effect is a departure from the additive law for the logarithms or the product law of the actual yield.

NEWMAN: Are interaction terms in the model?

HARTLEY: No interaction terms exist in the model for $\log y$, and no interactions exist between w and x. You are discussing what happens within a stratum.

NEWMAN: You will have different strata to account for the interactions.

HARTLEY: Yes, you have different strata, which would definitely account for interactions as you go from one stratum to the other.

NEWMAN: You made the statement that you did not want "normal" values in this model because of the stratum approach that you are using for the interactions.

HARTLEY: The interaction between environmental variables and fertilizer rates is not relevant to this question. This problem concerns environmental variables that are available early in the growing season and those that are available later in the growing season. If these variables are correlated, then you are doing better to fit a custom-made law for predicting the effect of the early environmental predictors by themselves rather than using the full law for early and late predictors and substituting the "normal" values for the late environmental variables.

FEYERHERM: For the past 4 months, a group at Kansas State University has been thinking of working with the $g(w)$ portion of a product model such as the one depicted in equation (10-1). We have considered the $g(w)$ to be a multiplicative model rather than an additive model, based on weather variables. For example, if I have two different weather variables, rather than adding them, I will multiply them.

HARTLEY: The multiplicative model is not excluded?

FEYERHERM: You are correct. We want to work on the $g(w)$. We want to learn the amount of variability and the reason for variability caused by weather. We want to proceed with the assumption that perfect weather will produce optimum yield, which will be plugged in for the $f(x)$. As we put weather variables into the model, we will delete them from the highest yield. We will define w_1 and w_2 weather variables together with parameter values. A simple function would be $e^{-\beta w_1}$. This function begins at one and goes to zero. If w is equal to zero, then the weather element for the crop is the best possible and does not delete from the yield. As elements worsen, they will be deleted from the yield. We would like to obtain parameters that are really constant over the entire world relative to the influence of weather on y. The data that we will use for the model is experimental yield data rather than data from the USDA. Because we have data available over a 50-year timespan, we hope to see the influence of the weather variables w_1 and w_2.

ROBERTSON: I would like to talk about the $f(x)$. For the past 2 years, I have been working at Swift Current, which is a research station that has done much fertilizer work. A soil chemist has been working on the availability of nitrogen, and a microbiologist has been working on the microbiology in the soil regarding the availability of nitrogen. The fertilizer recommendations were based on soil zones that

were really climatic zones. We used three curves for good climate, medium climate, and poor climate, not considering day-to-day or season-to-season weather variations, which did not work very well. We found that $f(x)$ is a function of applied fertilizer rate. However, the available fertilizer that the plant can use depends on weather conditions. Thus, this $f(x)$ is a function of weather as well as fertilizer application, and it must be modeled the way $g(w)$ is modeled.

HARTLEY: This good, medium, or poor weather is in a stratum where you would expect a certain type of weather. You recommend the correct amount of fertilizer, but, unfortunately, the weather changes on you. Supposedly, the model does account for the fact that the fertilizer uptake is more difficult if no moisture exists.

ROBERTSON: If I understood your model correctly, $g(w)$ is the effect of weather on yield, not on fertilizer availability.

HARTLEY: By fertilizer availability, do you mean uptake?

ROBERTSON: No, I mean availability, which is different. The availability varies with the weather. Uptake also varies, but the availability is the most important.

HARTLEY: Are you saying that putting availability into this product form is impossible?

ROBERTSON: The functions are different. Theoretically, adding water to the soil should increase growth. However, from our measurements, we learned that adding water to the soil lowers the availability of nitrogen because it leaches it out or makes it mobile.

HARTLEY: The $g(w)$ could be a product of two different functions.

ROBERTSON: The $g(w)$ is the plant growth product.

HARTLEY: Yes, but you can have a variety of products in the $g(w)$. The $g(w)$ is a function of the environmental data.

ROBERTSON: Has $g(w)$ affected yield separate from fertilizer? On the other side, $f(x)$ is your fertilizer; thus, you cannot mix them.

HARTLEY: Suppose that $f(x)$ is the response to the applied fertilizer rate x under your "medium" climate. If your $f(x)$ for "good" climate can be represented by the same $f(x)$ but increased by a computable percentage and if your $f(x)$ for "poor" climate can be represented by the same $f(x)$ but decreased by a computable percentage, then the three separate functions $f(x)$ can be written in the form

$h(w) \cdot f(x)$, where $h(w) = 1$ for the medium climate, $h(w) = c^+ > 1$

for the good climate, and $h(w) = c^- < 1$ for the poor climate.
We can now adjoin the function $h(w)$ with the $g(w)$ in our model
and write new $g(w) =$ old $g(w) \times h(w)$ and maintain my product
model. Of course, you may tell me that the Swift Current experi-
ence does not permit a representation of your three $f(x)$ func-
tions in the product for $h(w) \cdot f(x)$, not even approximately.

11. A CLIMATOLOGICAL ASSESSMENT OF EVAPORATION

By John F. Griffiths*

The climate of a region is expressed in terms of various component parts that can be measured directly. These parts, called elements, include aspects such as temperature, rainfall, relative humidity, and many others. Some elements that could be measured often are not — for example, light, soil moisture, and evaporation. When an organism such as a plant is introduced into the atmosphere, a complication occurs because the organism generally responds to a complex of elements rather than to a single element — in other words, a plant actually integrates the climate. It may seem unrealistic to attempt to express that response in the form of simple regression equations; however, a logical rationale could be that, actually, even air temperature is an integration of many climatic variables that, in turn, are integrated by the air.

Estimations of moisture involve both a gain and a loss concept because moisture is leaving as well as entering the system. Moisture gain is related to precipitation, whereas moisture loss is related to evaporation. Evaporation is basically a meteorological problem because it is concerned with a standardized measurement. This measurement is obtained from an open-water surface in a pan of a selected size.

Because of a shortage of evaporation stations, an interpolation process between stations was desirable. Texas A. & M. University began on the derivation of a method for determining pan evaporation from available information concerning other climatological elements — that is, an empirical relationship was developed between pan evaporation and climatic elements. The area investigated included 105 stations that covered over 1 million square miles, beginning west of the Mississippi River and ending as far north as the border of California. Most stations provided as much as 30 years data.

In all cases, a very high correlation (approximately 0.9), with a very small standard error, was obtained between mean monthly temperature and mean monthly pan evaporation. The correlation was increased by using mean monthly maximum temperature rather than mean monthly temperature; however, the increase was only fractional.

In some regions having a pronounced time lag between radiation and temperature, the use of mean monthly temperature for the preceding month was necessary. A time lag of approximately a month existed between maximum temperature and maximum radiation, depending on whether the climate was continental or marine. A time lag also existed between evaporation and temperature. However, if the temperature for the preceding month was included with the temperature for the present month, the time lag was almost zero.

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*Texas A. & M. University, College Station, Texas.

Maps were drawn, and scalar analysis of the regression coefficients was made in such a manner that interpolation was allowable for any region that had not been studied by direct measurement. This method can be used for the calculation of pan evaporation on a monthly basis. The calculated number can then be corrected to an evapotranspiration value and used in the total concept of a climatic index for soil moisture.

Other meteorological elements, such as windspeed and relative humidity, were examined. Windspeed was not an important element. Even at critical windspeeds, the evaporation did not increase very much. Relative humidity reflected a somewhat similar pattern to windspeed. If a high correlation coefficient is obtained from a large sample and if there is a small input of "so-called" independent variables, then this technique could be used.

QUESTIONS AND ANSWERS

HAUN: I would like to say in defense of all biologists who develop models that, actually, all models are abstractions. Whether you are a meteorologist or a biologist, you are looking for a compromise between the state of abstraction and the state of operation.

GRIFFITHS: I hope some of our abstractions will develop well enough to be put into a museum of science.

SUITS: Another source of moisture, dew formation, is as good as precipitation as far as plant growth is concerned. Do meteorologists report dew precipitation? How many inches of rain do you think dew precipitation recuperates from the atmosphere?

GRIFFITHS: In some of the most extreme areas of dew formation in the world, the Negev Desert, dew amounts to more than actual precipitation. In most places, a small amount of dew is measured per evening (fractions of a millimeter). The most important factor is that dew occurs at the time of best utilization. However, no inexpensive or easy way of measuring dew exists. Duvdevani blocks can be placed outside to see how much condensation forms on them. These blocks can then be compared with photographs, which is not an accurate measurement of dew formation. The precipitation gage is also not very accurate; however, it does not look obviously inaccurate.

BARGER: Fungus diseases very often establish themselves as a result of a given number of hours of wet foliage; thus, we must note both the negative and the positive effects of dew collection on wheat production.

TRACY: A colleague expresses the opinion that dew does not come from the atmosphere but percolates up from the soil. Thus, dew may not be additional moisture available to the plant.

GRIFFITHS: In 1957, a classic paper by Monteith differentiated between the two types of dew and showed that dew both rises and falls.

12. USE OF ERTS-1 FOR DETERMINING GROWTH AND PREDICTING

DISEASE SEVERITY IN WHEAT

By Edward T. Kanemasu*

The objectives of the Earth Resources Technology Satellite 1 (ERTS-1) project at Kansas State University were to evaluate the effects of water stress, disease, and leaf area on the reflectance characteristics of wheat, to evaluate disease losses in terms of yield and water use, and to predict disease severity and economic loss. The study was designed for winter wheat in Kansas, which is the leading state in wheat production. Wheat accounts for approximately 60 percent of the total crop receipts in the state. The five test areas in Kansas are depicted in figure 12-1. These areas were selected because of their proximity to agricultural experiment stations and/or fields and because of their history of disease incidents. This report is concerned with the Garden City area (Finney County), which has a history of disease losses, and the Manhattan area (Riley County), where two data collection platforms were located.

A black and white print of a normal color, low-altitude (5000 foot) photograph of a wheatfield infected with a soilborne mosaic virus is shown in figure 12-2; the disease appears as very light spots in the field. A black and white print of a color infrared (IR) photograph shows the same area; the diseased spots are light, whereas the healthy wheat is dark (fig. 12-3).

The objective of the study was to detect these diseased areas by using the ERTS-1. The solar radiation spectrum (wavelength as compared to spectral density) and the spectral wavelengths of the multispectral scanner (MSS) bands aboard the ERTS-1 are shown in figure 12-4. Bands 1 and 2 (referred to as MSS bands 4 and 5) are in the visible wavelengths, whereas bands 3 and 4 (referred to as MSS bands 6 and 7) are in the near IR. Data taken from an ERTS-1 pass on May 13, 1973, over the Finney County area determined the yields on approximately 50 to 60 fields (table 12-I). Each field was rated in terms of disease severity on a scale of 0 (healthy) to 3 (severely diseased). Healthy fields usually yield more than diseased fields. However, this assumption is not always true, which illustrates that yield is affected by many factors other than disease. The digital counts and standard deviations for the fields are shown for MSS bands 4, 5, 6, and 7. An increase occurs in the digital counts with increasing disease severity for MSS bands 4 and 5 (the visible wavelengths).

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*Kansas State University, Manhattan, Kansas.

One portion of this study was the prediction of disease severity. Using the fungal growth function and meteorological data, the Epidemiological Laboratory at Kansas State University has developed equations that predict the severity of a disease 30 days in advance. The data collection platforms provided by NASA were placed in commercial wheatfields, and these meteorological data were transmitted to the ERTS-1 twice daily (fig. 12-5). The antenna and the large white box housing the transmitter and electronic interface are illustrated in figure 12-6. A lead storage battery supplied the power. The visible and near-IR radiation sensors were on the nearby stand. The temperature and humidity sensors were contained in the small white box. The ERTS-1 came within range of the transmitter on three revolutions centered at approximately 10:20 a.m. c.s.t. and 10:20 p.m. c.s.t. Relative humidity, hours free from moisture, minimum and maximum temperatures, instantaneous temperature, incoming visible radiation, reflected visible radiation, incoming near-IR radiation, and reflected near-IR radiation were transmitted during these two time periods. These meteorological data and the fungal growth function were used to predict the severity of the disease and the subsequent yield reduction. If the yield reduction was large, the grower should have plowed under the diseased wheat and planted a following crop. The earlier he plowed under the diseased wheat, the better his chance for a successful follow-up crop because of the conservation in soil water. The pattern of water use of five wheatfields is shown in figure 12-7. Over the entire growing season, the crop water use was approximately 80 centimeters. Approximately 40 centimeters of water were used by the end of March. If the grower plowed under his diseased wheat by mid-April, he could conserve approximately 10 centimeters of water, which could be available for the following crop.

A second portion of this study was to investigate the reflectance patterns of wheat throughout the growing season and to correlate this reflectance with growth. A hemispherical spectroradiometer was used to measure the canopy reflectance. The spectral reflectance of wheat at various growth stages is depicted in figure 12-8. On May 16 (heading stage), the spectral reflectance curve shows a peak in the visible wavelengths at 550 nanometers (green) and a high reflectance in the near-IR wavelengths at 750 nanometers. This curve is typical for a closed canopy — that is, a strong absorption by the plant pigment (chlorophyll) occurs in the blue and red wavelengths. The high near-IR reflectance is due to the multiple reflections that occur within plant leaves. Because of the high reflectance and transmittance of plant leaves, the near-IR reflectance increases with increasing leaf density. Note that the reflectance at 650 nanometers shifts up or down, depending on crop cover or living leaf area. During the heading stage, much leaf area exists, and the reflectance at 550 nanometers (corresponding to MSS band 4) is higher than at 650 nanometers (corresponding to MSS band 5). During the dormant (February) and hard-dough stage (June), very little living leaf tissue exists, and the reflectances at 550 and 650 nanometers are nearly equal. Regardless of surface moisture, the reflectance for bare soil at 650 nanometers is greater than at 550 nanometers (fig. 12-9). Therefore, the ratio of the reflectances from 500 to 650 nanometers will indicate the vegetative density — that is, a ratio less than unity will indicate a low density, whereas a ratio greater than unity will indicate an increasing density. This reflectance ratio is shown throughout the growing season (fig. 12-10). The reflectance ratio does not significantly change when soil moisture changes.

A linear-regression equation of leaf area index (LAI) and percent cover as compared to the reflectance ratio and the percent near-IR reflectance is depicted in table 12-II. The LAI is the ratio of leaf area to soil area. The ERTS-1 data for the same wheatfields viewed by the spectroradiometer were correlated with LAI and percentage cover; data were obtained by eight ERTS-1 passes during the growing season. Linear-regression equations using MSS bands and LAI are shown in table 12-III. A better indicator of crop growth is the ratio of MSS band 4 to band 5, which is consistent with the ground-based spec-troradiometer data. Apparently, because of the relatively low LAI (2 to 3) of wheat, soil and leaves appear, whereas higher LAI (6 to 10) crops show complete leaf cover. Hence, the ratio of MSS band 4 to band 5 is a good indicator of LAI or percent cover.

QUESTIONS AND ANSWERS

SMITH: Do you have any idea what the LAI for your wheat range up to 3 and 4 transcribes to in terms of grams per square centimeter of dry biomass?

KANEMASU: No, but we did measure dry matter production in milligrams per square centimeter, which I can obtain for you.

SMITH: Could you look at the interchanging channel ratio correlation with percent green or time development of the wheat?

KANEMASU: Percent cover is obtainable.

SMITH: You have LAI and correlation with different channel ratios. Was that the average over the entire season?

KANEMASU: Yes.

SMITH: You have not broken down LAI by growth in terms of percent green?

KANEMASU: No.

ROBERTSON: What was the earliest date that you could recognize wheat?

KANEMASU: Are you referring to the study at the University of Kansas?

ROBERTSON: Yes.

KANEMASU: The investigators used winter wheat, which is normally planted in October, and they used September imagery because the fields are plowed during this time; thus, they used the dark-colored fields for identification.

ROBERTSON: You are not really recognizing wheat. How early can you distinguish between wheat, oats, and barley in the developmental life stage of these plants? Can a distinction be made between these three crops?

KANEMASU: To separate and to identify signatures of the various crops was beyond the scope of the project. Many crops are very hard to distinguish. You just do not measure the spectral reflectances of crops and separate them.

PITTS: You mentioned that some of your data were collected in the field. Were some of the data actual ERTS-1 imagery?

KANEMASU: Yes, data shown in table 12-III are from eight ERTS-1 passes during the entire growing season of the wheat.

PITTS: The soil spectrum appears to be fairly gray, whereas the wheat
              spectrum is nongray throughout the growing season. Furthermore,
              the soil moisture did not spectrally perturb the grayness of the
              soil as it appeared in the ERTS-1 channels. Is this fact what
              actually allows you to distinguish between the two spectra by
              using the ratio of MSS band 4 to band 5?

KANEMASU: Yes.

HARLAN: Two joint experiments between NASA and Texas A. & M. University are
              being conducted this year. These experiments will help determine
              the spectral characteristics of wheat, barley, and rye; thus, we
              will see what time differentiation is possible strictly from
              spectral characteristics.

TABLE 12-I.– DIGITAL COUNTS TAKEN FROM MSS BANDS[a]

Disease severity (b)	Yield, bu/acre	Digital counts ± standard deviations			
		MSS 4	MSS 5	MSS 6	MSS 7
0	29.5	32.95 ± 2.23	27.08 ± 3.52	52.46 ± 6.46	30.49 ± 5.27
1	31.6	32.49 ± 4.63	26.07 ± 5.50	50.86 ± 12.68	29.61 ± 8.75
2	25.6	40.40 ± 10.51	36.50 ± 12.39	57.35 ± 8.29	31.66 ± 5.41
3	20.8	44.02 ± 15.60	39.43 ± 17.21	59.97 ± 10.88	32.77 ± 5.27

[a]The ERTS-1 pass over Finney County on May 13, 1973.

[b]Ratings of disease severity are given from 0 (healthy) to 3 (severely diseased).

TABLE 12-II.- LINEAR-REGRESSION EQUATIONS AND
CORRELATION COEFFICIENTS FOR WHEAT

Linear regression equation	Correlation coefficient
LAI = 5.06 × reflectance ratio − 4.07	0.75
LAI = 0.13 × percent near-IR reflectance − 1.67	.54
Percent cover = 109.88 × reflectance ratio − 63.71	.87
Percent cover = 2.85 × percent near-IR reflectance − 19.24	.72

TABLE 12-III.- LINEAR-REGRESSION EQUATIONS OBTAINED

FROM ERTS-1 PASSES OVER FOUR WHEATFIELDS IN KANSAS

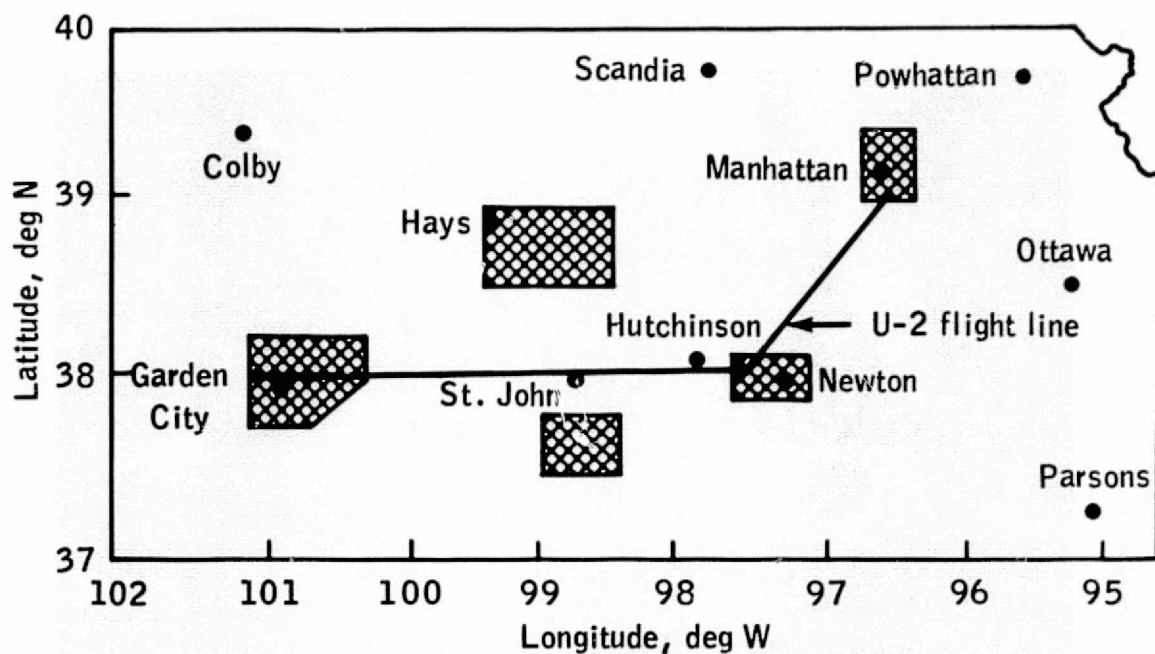| Linear regression equation (a)	Correlation coefficient
LAI = 3.305(MSS 4/5) − 3.089	0.92
LAI = −3.395(MSS 4/6) + 3.275	−.72
LAI = −1.384(MSS 4/7) + 2.650	−.73
LAI = −3.034(MSS 5/6) + 2.804	−.90
LAI = −1.307(MSS 5/7) + 2.402	−.87

[a]The MSS band ratios of their respective digital counts.

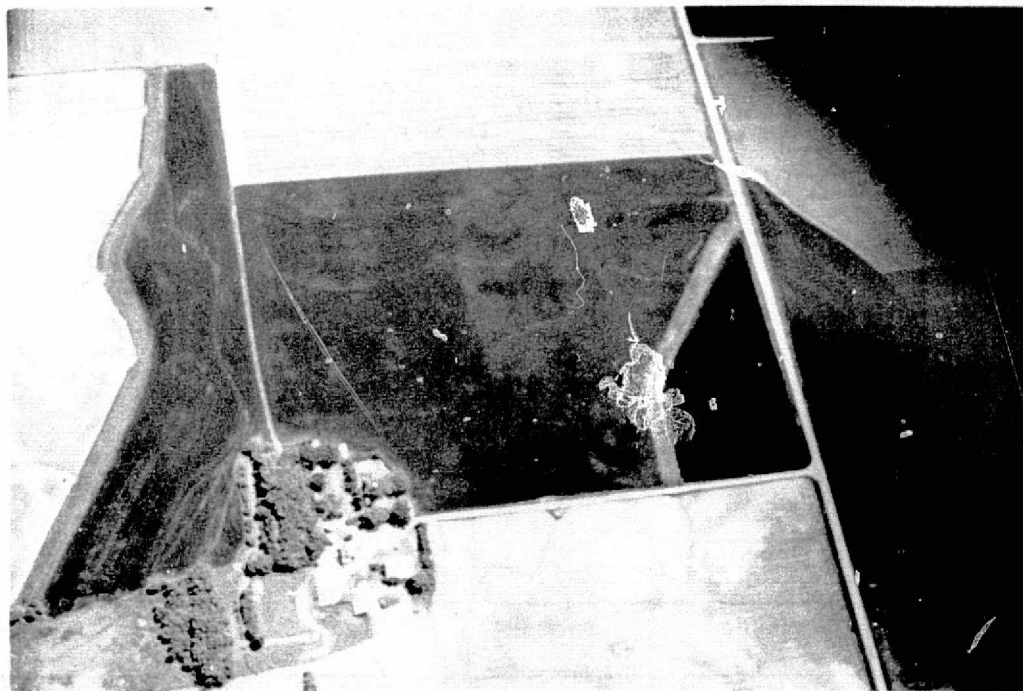Figure 12-1.- Location of the five test areas and the experiment stations in Kansas.

Figure 12-2.- A black and white print of a normal color, low-altitude (5000 foot) photograph of a wheatfield infected with a soilborne mosaic virus.
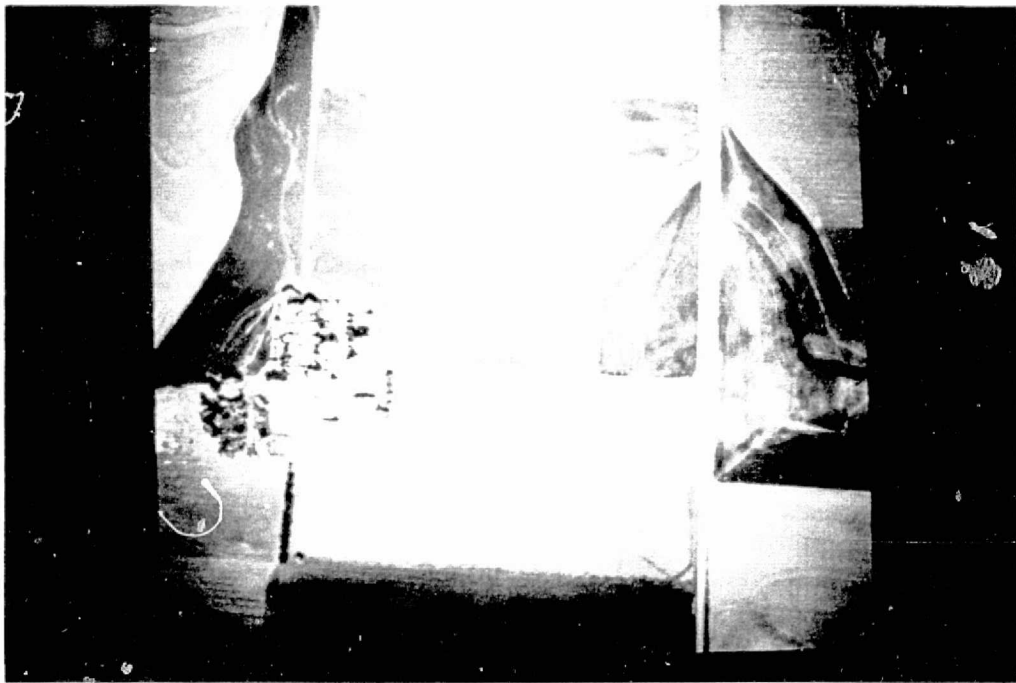
Figure 12-3.- A black and white print of a color photograph of a wheatfield infected with a soilborne mosaic virus.
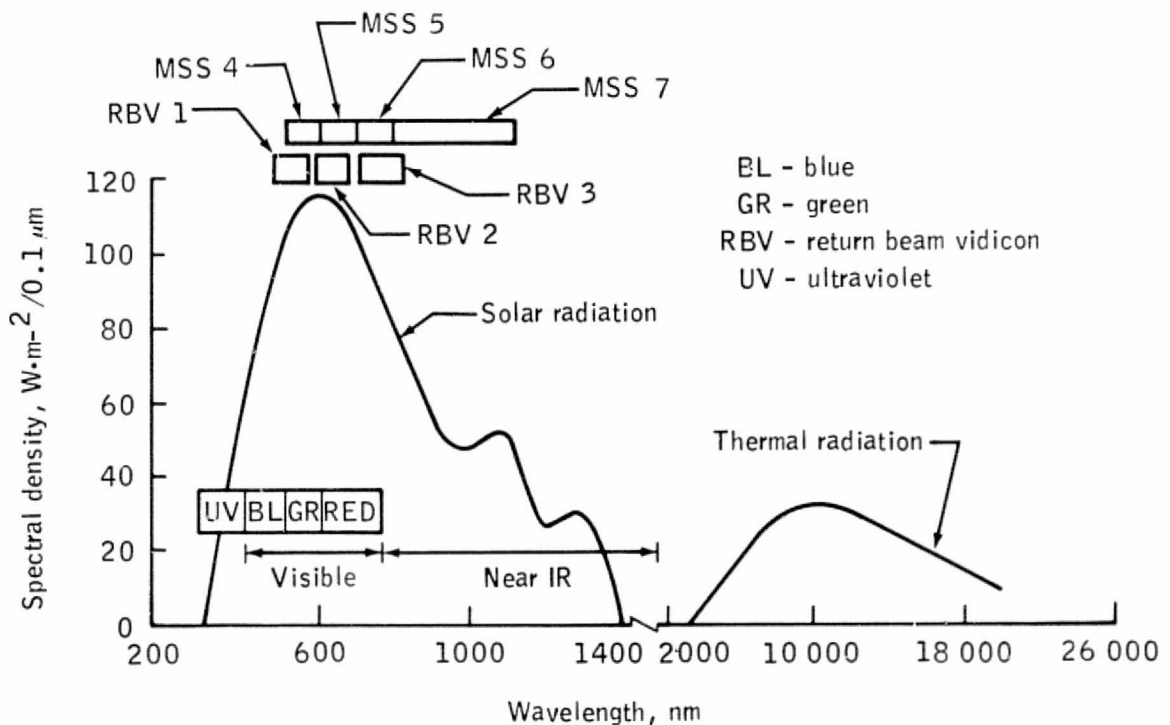

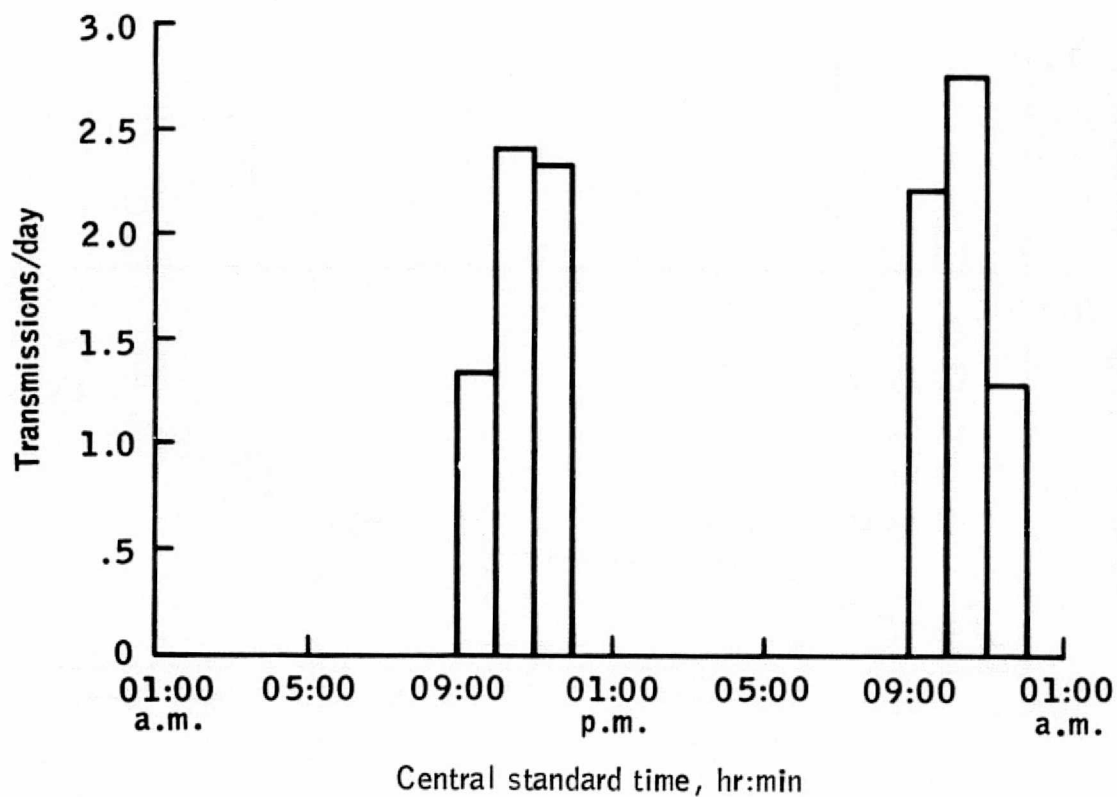Figure 12-4.- Solar radiation spectrum and the spectral wavelength of the MSS bands.

Figure 12-5.- Frequency of the data collection platform meteorological
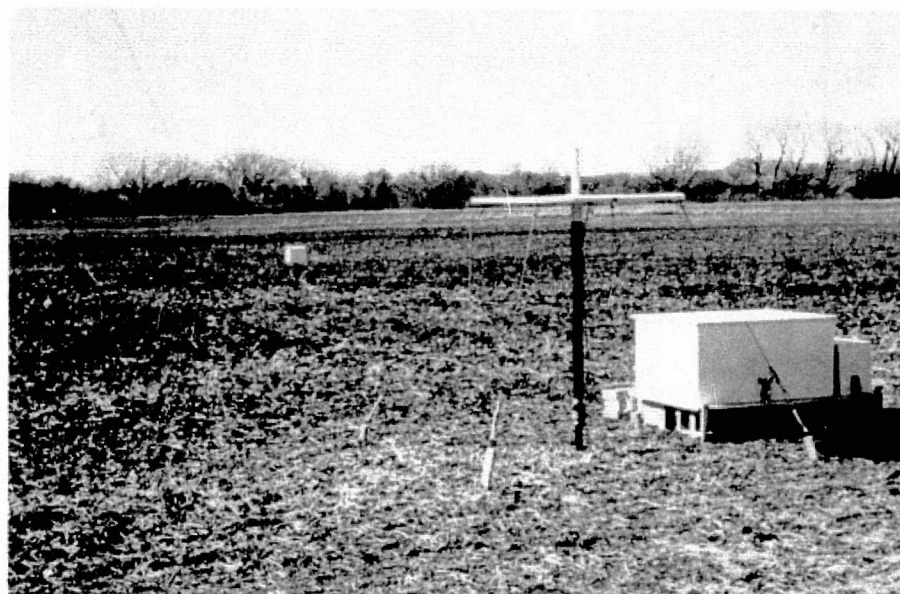data transmitted to ERTS-1.
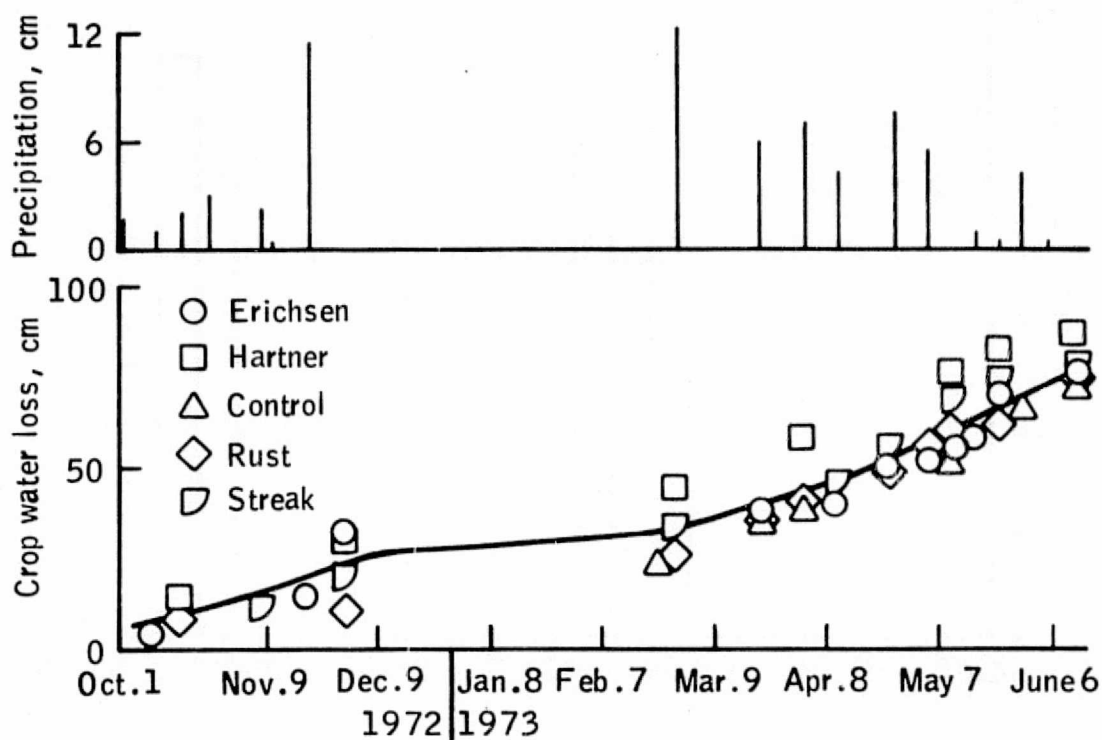

Figure 12-6.- Data collection platform.

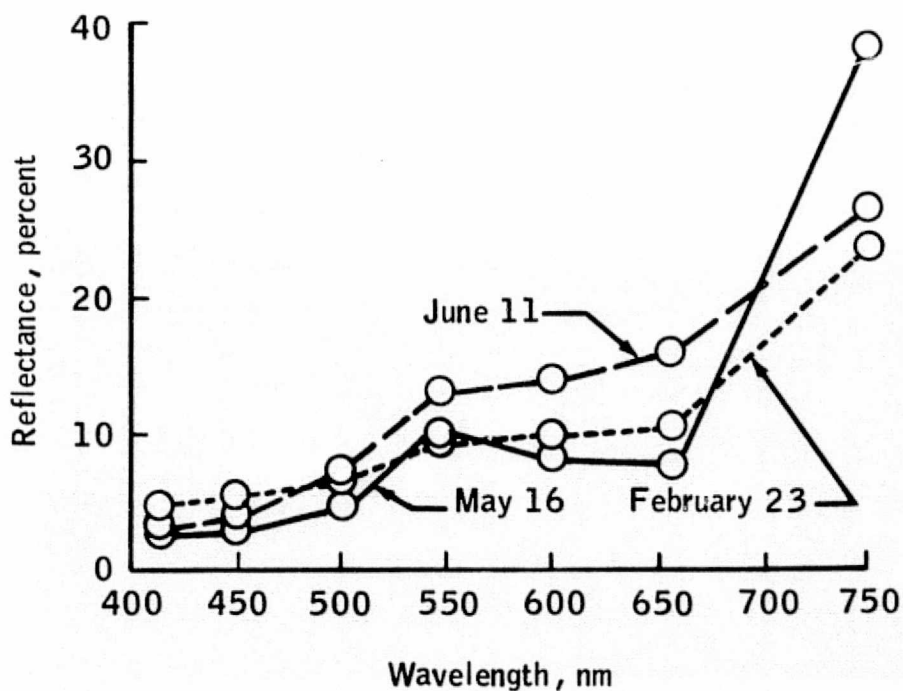Figure 12-7.- Pattern of water use in winter wheat.

Figure 12-8.- Spectral hemispherical reflectance of winter wheat
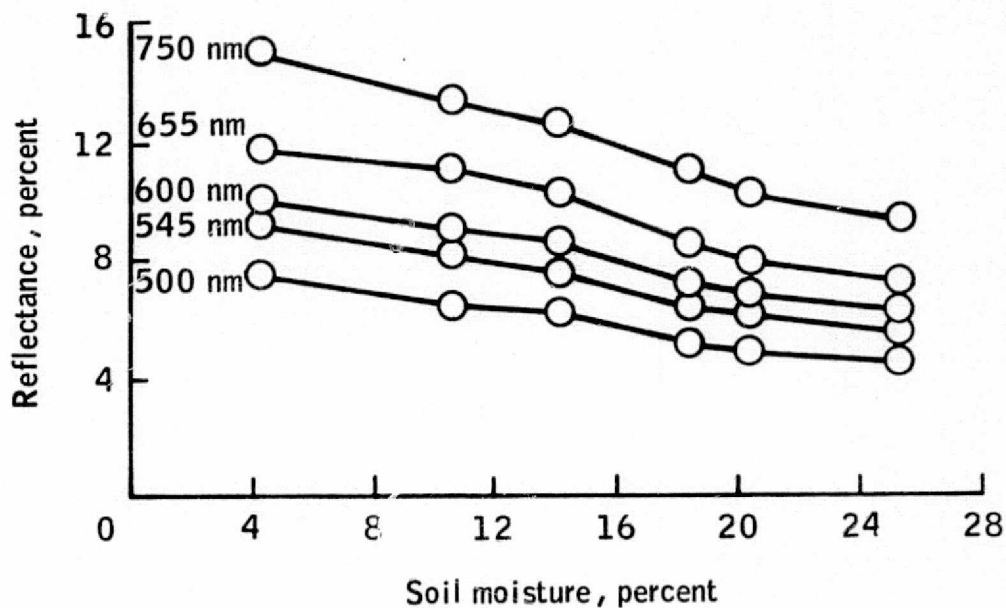at various growth stages.

Figure 12-9.- Spectral reflectance of bare soil at various surface moisture contents.
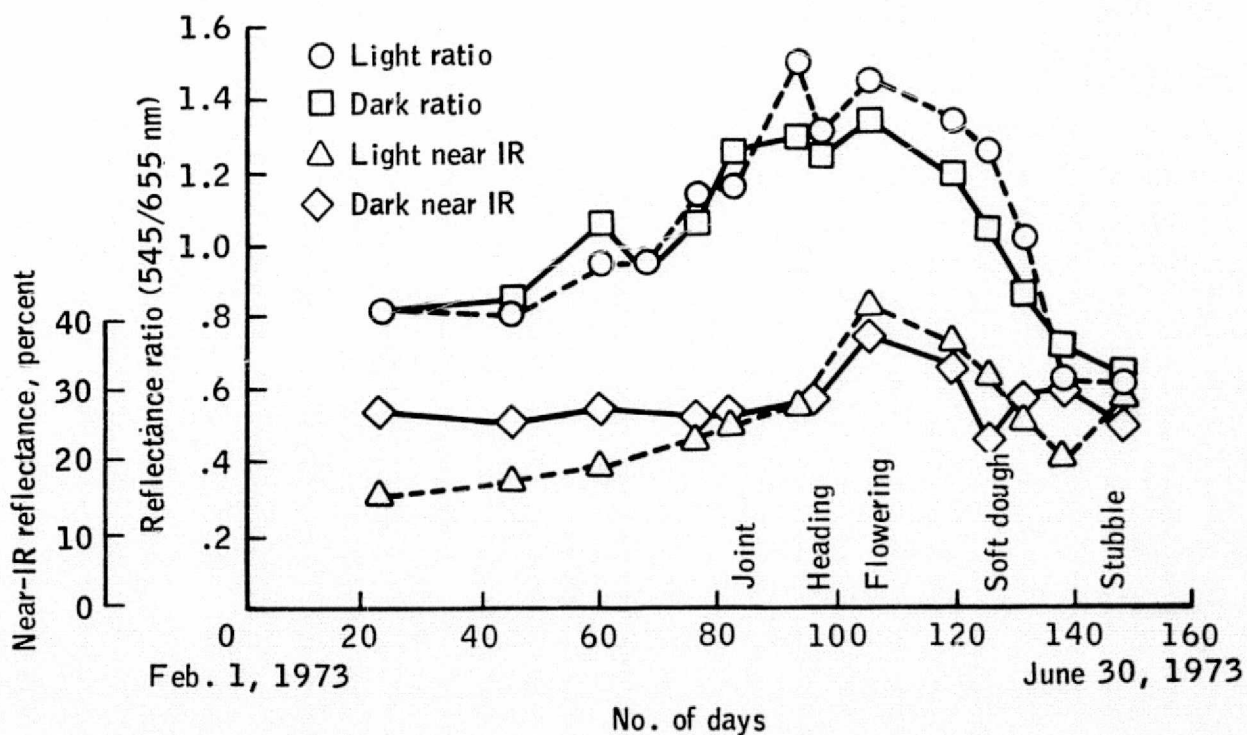

Figure 12-10.- Seasonal trends in the reflectance ratio (500 to 650 nanometers).

12-13

13. PERCENT GREEN AS AN INDICATOR OF BIOMASS AND PHASE DEVELOPMENT

By Charles M. Jones[*]

Many data have been assembled during the past 10 years representing ground-truth observation. From this information, the solar thermal unit (STU) theory has been developed, which is composed of two multiplied factors. The first factor is the amount of solar radiation in langleys per day. The second factor is an average of the maximum and minimum temperatures that contains a threshold temperature, which will make the entire equation result in zero on any day when that threshold temperature is not exceeded.

$$STU = \sum_{T_e > 0} (R)(T_e) \tag{13-1}$$

where R is solar radiation in langleys per day and T_e is daily $\frac{T_{max} - T_{min}}{2} - T_{thres}$. The summation of the solar thermal unit is done on a daily basis and corresponds to a bioclimatic scale to represent the growth stage of a plant as the season progresses. If enough nutrients and water are available, the STU theory will indicate when different changes in the developmental stages of plant growth are expected. Thus, temperature (above the threshold temperature) can compensate for reduced solar radiation, and solar radiation can compensate for reduced temperature.

The first experimental plant was the common purple lilac. The first leaf begins when a certain number of STU's have accumulated. Statistical analysis was used to determine the threshold temperature, which should be 31° F. According to the STU theory, the first bloom for the common purple lilac would occur when approximately 380 000 STU's have accumulated, and alfalfa would be ready to cut (approximately 10-percent bloom phase) when approximately 820 000 STU's have accumulated. A list of approximately 24 different plants has been compiled that defines the developmental stages and the required number of STU's. Worldwide maps based on this principle will indicate the total annual potential alfalfa cuttings, if these cuttings are accomplished when 820 000 STU's have accumulated. To obtain potential evapotranspiration in inches, the STU number is multiplied by 10^{-5}.

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[*]Montana State University, Bozeman, Montana.

Montana State University has been participating in the phenology satellite experiment, which encompasses two parts of the United States: the eastern and the western sections. The eastern part contains two corridors or areas with ground stations. The western portion also contains two corridors that have a total of 10 major stations. Each of these western stations has at least three ground-truth substations; thus, more than 30 test plots are scanned by the satellite. Data obtained from multispectral scanner (MSS) bands 4, 5, 6, and 7 are used. These ground-truth stations are photographed by observers every 6 days, and these 6-day intervals are synchronized with the 18-day satellite passes. Thus, both horizontal and approximately vertical ground-truth photographs have been taken of wheat, range grass, and alfalfa at each of the western test sites.

The first western corridor, the Rocky Mountain corridor, starts at Browning, Montana, and runs approximately southward through Idaho, Utah, and into Arizona. The second western corridor, the Columbia Valley corridor, also starts in Montana and runs approximately westward through the Columbia Valley toward the Pacific coast. These two corridors have different elevations. The Rocky Mountain corridor is approximately 4700 feet, whereas the Columbia Valley corridor is approximately 3000 feet. However, all the sites in a corridor are approximately the same altitude; thus, the sites should be somewhat homogeneous in their output.

By using the ability of the STU theory to predict when critical phases should be reached, certain areas of wheat production could be scanned by satellite. Thus, by using the meteorological data (temperature and radiation), the length of time that wheat production should remain in a certain stage could be predicted. Critical stages of wheat production would be related to changes in color reflectance. These critical stages probably would not correspond exactly to the five normal stages of wheat growth.

Data received from satellite passes over these test sites proved that alfalfa is easily recognizable. Thus, an alfalfa field can be recognized by a particular response curve (fig. 13-1). The MSS band 4 is the so-called green channel. An original intent was to determine the percent green or the green wave by a satellite pass over the ground-truth station and to compare this information with the observations of ground observers. The MSS band 4 is probably as sensitive to yellow as it is to green; thus, it would include both the green and yellow channels. The MSS band 5 includes both the orange and red channels; MSS bands 6 and 7 are the near-infrared channels. Because both green and yellow comprise MSS band 4, to recognize the stage when the wheat plant is changing from a predominantly green color to a predominantly yellow color is difficult. In predicting wheat yield, this color change is a very important stage. Orange is also very predominant when that change of color first begins. When the farmer cuts the alfalfa, the soil appears as a lower percent green, and this response curve would appear much different. A strong rise in MSS band 5 intensity would be evident. The near-infrared MSS band 7 would have a strong tendency to drop. Moreover, MSS band 4 would have a strong tendency to drop, whereas MSS band 5 would rise.

Because some difference exists in the reflectance from various crops, a difference should occur in these spectral responses. A processing report for

13-2

each test plot has been used. Each report encompasses a specified test plot and includes a graph of the spectral response. Also included in the reports is a statistical analysis of the situation. A typical wheat-plot curve is shown in figure 13-2. The shape of the range-grass-plot curve shown in figure 13-3 is very similar. Perhaps all monocot narrow-leaf plants of any kind will produce this same spectral response. However, in the early stages of wheat in which light green occurs, MSS band 5 has a tendency to drop, and MSS bands 6 and 7 will rise; thus, the wheat-plot curve would be somewhat similar to the alfalfa-plot curve shown in figure 13-1.

The expertise exists to determine and to identify the areas where the particular crop is being grown. After the area has been identified, spectral-response data could be used to indicate whether the plant has had an opportunity to develop through its normal growth interval (accumulation of STU's) before changing its spectral response because of inadequate moisture or nutrients. According to these spectral-response data, if the plant did not remain in that particular growth phase long enough, prediction on the total yield throughout the growing season should be downgraded. Therefore, both the STU theory and spectral-response data should be used to predict yield.

To obtain percent green, a band ratio parameter (BRP) was used, which is the difference between MSS bands 7 and 5 divided by the sum of MSS bands 5 and 7. Hopefully, this BRP formula and other formulas will allow the use of satellite data to indicate percent green of various crops or plant communities. To develop the necessary formulas, ground-truth information is needed for various crops. This information could be used to develop identification formulas for crops such as wheat.

In the spring, as evidenced in the ground truth for an alfalfa field, the percent green increases almost linearly until the alfalfa reaches approximately 12 inches. Thereafter, the percent green somewhat asymptotically approaches 100 percent. When the alfalfa reaches approximately 14 inches, the 100-percent-green cover is achieved even though growth continues. The leading edge of the percent-green response curve for other crops, such as wheat or range grass, will usually not attain a 100-percent-green cover. Thus, these response curves are generally linear in early spring.

Other formulas that will use all four bands are being developed. These formulas will be more crop specific and will do a better job than the BRP formula for individual crops. However, as an indicator of the growing season or green season, the BRP formula does quite well for all foliage. The values for the BRP formula are approximately the same at a given percent green for either wheat or alfalfa; however, the value of the BRP formula for range grass would correspond to a much lower percent green.

Seven experts looked at each of the ground-truth photographs and plotted the percent green for each observation. This information was used as ground-truth reference for comparison with the satellite data. The BRP formula for percent green correlated rather closely with the percent green seen from the ground-truth photographs. Moreover, the correlation was close enough to be useful as a green-wave indicator.

QUESTIONS AND ANSWERS

HARTLEY: Is that response the average spectral response for alfalfa?

JONES: Yes, on that particular occasion from that particular image.

HARTLEY: If you are looking at the variations for wheat fields as compared to the variations for alfalfa fields, do you obtain a difference in variation between the two sites?

JONES: Yes, we do. I cannot give you the exact amount of variation. Variations in the response for wheat seem to be slightly greater than those for alfalfa.

ROBERTSON: What is the acreage of your fields?

JONES: Approximately 40 acres is the largest area, and 8 acres is the smallest area. To get the computer to home in on such a small area is very difficult. The farmers tend to lay out their fields on a north/south grid. However, the scan lines that come from the satellite do not lie on a north/south grid.

ROBERTSON: Do you receive and use information from each pixel?

JONES: We group the entire plot. We tell Texas A. & M. University the entire outline of our area, and we pick a rectangle. From that information, they produce this processing report.

ROBERTSON: Do you receive any information indicating variation of data among pixels?

JONES: No, Texas A. & M. University does not tell us the radiance values for each pixel because they are much too small for us to use.

PITTS: Even though the spectra may be similar, if any one of the four bands has a different standard deviation, the two crops would separate and permit identification.

MACDONALD: In the 1964-65 period, people began recognizing that you could not differentiate various kinds of green vegetation by looking only at the mean. The secret of most classifications is to note the variation of the measurements.

THOMAS: Some statistical procedures are available that allow you to use a number of pixels in a training field to develop standard deviations and so forth to evolve centers of mass for given MSS band points. Using the Wilcox rank statistical test procedures, you can test to see if a significant difference occurs between the reflectance and the given MSS band. Moreover, you can combine these various MSS bands into an n-dimensional space and test to see if a significant

difference exists between the n-dimensional masses. You can thereby differentiate between different crops in an n-dimensional space. In certain cases, fairly high accuracies of identification can be obtained at relatively vegetated growth stages for several of the crops that we are considering. The spectral reflectance value for a given pixel is measured. Also, a population of pixels is specified for a given training field. Obviously, standard deviation and mean can be calculated by appropriate statistical procedures to test for the difference in variations. Those crops can be differentiated within a given MSS band, a series of MSS bands, or the ratios of MSS bands. Extending this information to parameters other than spectral features, the same method applies in n-dimensional space with soil moisture, radiation, and so forth to improve the accuracy of crop identification and yield processes.

JONES: I have with me several maps of the Western United States that show the total number of days in the growing season, the green wave and when the growing season starts, and the brown wave and when the brown season ends. Of course, the green wave and the brown wave will be different for various crops.

PITTS: In MSS band 7, alfalfa has a very wide distribution and very large standard deviation, whereas corn has a very narrow deviation. In fact, these crops have quite different means. Alfalfa distribution in MSS bands 6 and 7 is quite large. What is the physical basis for using the BRP formula?

JONES: I cannot answer that question. Texas A. & M. University also uses this same BRP formula in another equation to relate it even closer to percent green by taking the square root of BRP plus 0.5. Obviously, the BRP formula is a very good representation of percent green.

PITTS: The process seems very similar to taking a ratio of two MSS b. 3s. The BRP formula could be, to some degree, a procedure to normalize the reflectance difference in two bands by the total energy incident on the crop.
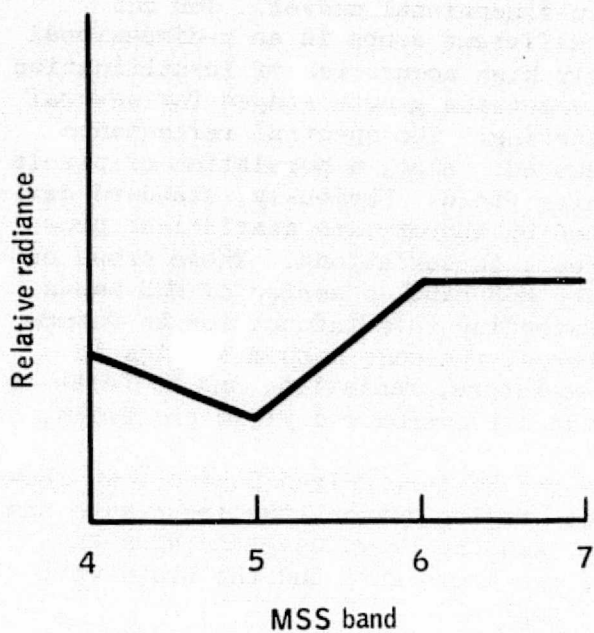
Figure 13-1.- Typical response curve
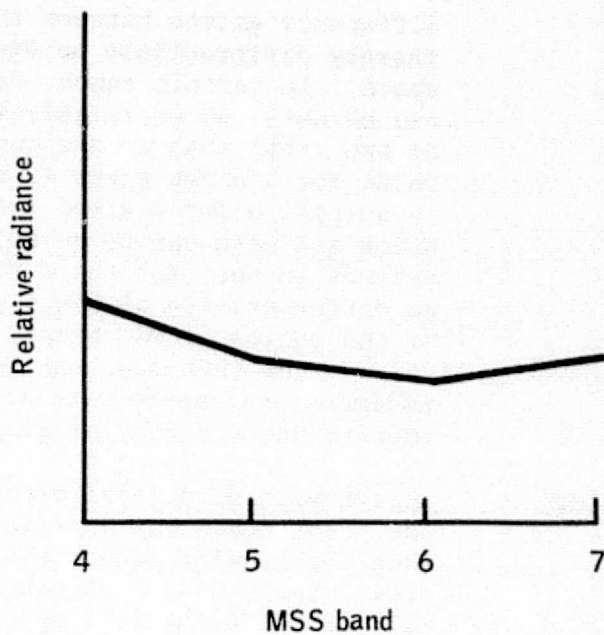from an alfalfa field.

Figure 13-2.- Typical response curve
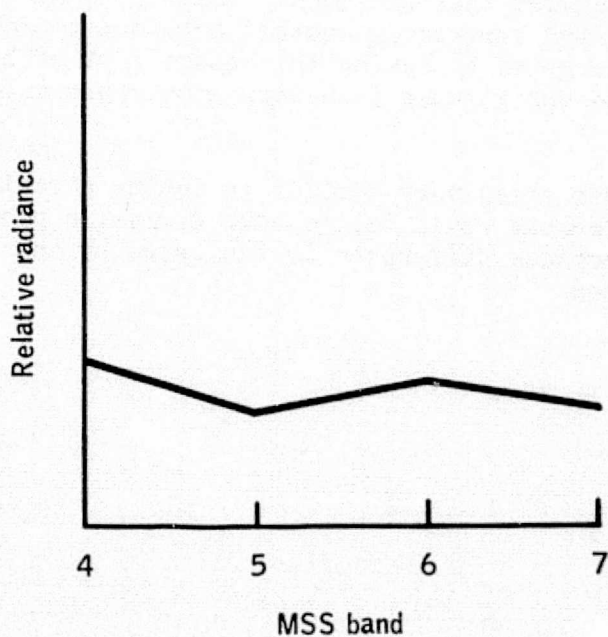from a wheatfield.

Figure 13-3.- Typical response curve
from a range grass field.

14. CANOPY MODELING FOR RELATING SCENE ATTRIBUTES TO REFLECTANCE

By James A. Smith[*]

Colorado State University has recently been involved in canopy modeling to better understand the interaction between light and vegetation. Initial experiments related biomass to reflectance ratios. Presently, an attempt is being made to map biomass classes by using Earth Resources Technology Satellite (ERTS) data. These projects have been conducted at the Pawnee National Grassland, the intensive study site of the U.S. International Biological Program grassland biome. Blue grama and western wheatgrass are the dominant vegetation types.

FIELD MEASUREMENTS

Initial spectral measurements were taken with a field trailer equipped with an EG&G spectroradiometer system, which had very good spectral resolution and fairly good sensitivity. The instrument was pointed through an aperture in the trailer onto a mirror and then down on the target surface. These data were adequate for the initial model development; however, obtaining data from many test plots for different view angles and different Sun angles was cumbersome. To extend the modeling effort, a much simpler system was developed that used snap-on interference filters. Thus, high spectral resolution was exchanged for portability. Two probes are used: one probe is pointed at a barium sulfate white panel, and the other probe is pointed at the target scene at the desired angle. The canopy response is obtained at selected spectral wavelengths rather than a continuous spectral curve. Other collected field data include leaf area index (LAI), biomass, leaf angles, chlorophyll content, and leaf water.

EXPERIMENTAL RESULTS

Pearson's results (ref. 14-1) were obtained by performing spectral measurements and biomass sampling on 112 25-meter-square test plots. The measurements were made on living vegetation in the field, but they were taken under artificial illumination. Although shadows are a significant problem for applications, the use of artificial illumination eliminated this problem and extended the amount of time available for gathering data. The relationship between the chlorophyll content of the test plot and the reflectance in the chlorophyll

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absorption band is shown in figure 14-1(a). As expected, reflectance decreases as chlorophyll content increases.. The relationship between leaf-water content and reflectance in the 0.78-micrometer wavelength band is depicted in figure 14-1(b). As the amount of intercellular water/air spaces increases, scattering and reflectance increase.

By relating leaf water to chlorophyll and by using these two relationships, Pearson related green biomass to radiance (or to reflectance ratio) in the two wavelength bands shown in figure 14-2. A strong linear trend occurs for medium biomass ranges; however, the relationship becomes nonlinear and probably flattens out for large biomass ranges. Generally, a much poorer relationship was obtained between total dry mass and radiance ratio (fig. 14-3). As the proportion of dry-to-green biomass increases, the correlation with radiance ratio decreases. This observation was also strengthened by applying these techniques to aircraft-level imagery. In the fall of 1968, a flight was made over the Pawnee National Grassland. Better results were obtained by using multispectral pattern recognition than by using ratio mapping. The objectives of the modeling effort are to predict experimental relationships and to correct for the effects of scan angle, shadowing, mixtures, phenology, and so forth.

MODELING APPROACH

A model schematic of the Monte Carlo approach is presented in figure 14-4. A physical or mechanistic-type model is being used rather than a regression model. The approach is a detailed bookkeeping method for ray tracing through the plant canopy. The approach is unique in that the stochastic nature of the processes and variables allows the prediction of both a mean spectral response and a covariance matrix. Inputs to the model include direct and diffuse irradiance, canopy geometry, and leaf and soil optical properties.

These parameters are difficult to measure in the field. Currently, some sensitivity tests are being conducted that relate model output to model input. For example, perhaps taxonomic descriptions for broad categories could be used for each model application rather than measured vegetation structure. A set of such distribution functions is presented in figure 14-5 (ref. 14-2). Erectophile vegetation contains mostly vertical leaves, whereas planophile vegetation contains mostly horizontal leaves. The dotted line is the measured distribution for the blue grama plots. The result of a leaf distribution test for canopy reflectance at a wavelength of 0.4 micrometer is depicted in figure 14-6. The leaf distribution numbers given in figure 14-5 are plotted along the horizontal axis.

CONCLUDING REMARKS

The significance of both scan-angle and Sun-angle variations in canopy reflectance in pattern recognition is being examined. To accomplish this task, model inputs are varied and spectral scatter plots for canopies are generated.

For example, the results obtained from two canopies differing only in LAI for two different scan angles is illustrated in figure 14-7 (ref. 14-3). At each scan angle, the best two wavelength channels for separating the clusters have been plotted. The separability of the two clusters, which corresponds to different biomass classes, as a function of scan angle for two different solar positions is quantified in figure 14-8. All wavelengths were in the visible portion of the spectrum. This variation in discrimination information for different targets as a function of scan angle and solar position is particularly important for aircraft scanner data; however, it may not be very relevant to ERTS, which has a small scan angle alined nearly vertically with respect to the surface of the Earth.

REFERENCES

14-1. Pearson, Bob: Remote Multispectral Sensing of Biomass. Ph. D. Thesis, Colorado State University, 1973.

14-2. De Wit, C. T.: Photosynthesis of Leaf Canopies. Agric. Res. Rept. no. 663, Inst. Biol. Chem. Res. on Field Crops and Herbage (Wageningen, Netherlands), 1965.

14-3. Smith, J. A.; and Oliver, R. E.: Effects of Changing Canopy Directional Reflectance on Feature Selection. Appl. Opt., vol. 13, no. 7, July 1974, pp. 1599-1604.

QUESTIONS AND ANSWERS

BEETH: This variation is relevant to ERTS if you go from pass to pass because you obtain over a 30° change in solar elevation during a wheat-growing season. However, I do not know how to interpret this relevance.

SMITH: Yes, you are correct.

TRACY: Do you receive a diffuse radiation that travels from the ground to ERTS? Is the location of the Sun relative to the crop that you are photographing important? Also, is a different view or different spectral signature caused by looking downward rather than sideward that important? Does the effect of wind on crops make that much difference? One picture every 18 days should give you some of this type information.

SMITH: I view modeling as a coupler between what is seen by the sensor and scene characteristics. All these factors matter; however, the question arises as to what extent and under what circumstances. In obtaining aircraft data, the scan angle is of tremendous importance. Historically, we have flown near solar noon on clear days. Sometimes, empirical functions have been used to correct the data.

TRACY: Reflectance should vary with gross climatic differences.

KNEMASU: Are the ratios of reflectance used for biomass estimation sensitive to the scan angle?

SMITH: We do not have this information because of the breakdown of our model at the chlorophyll absorption band, which is one of the wavelengths used for biomass mapping that uses ratio techniques.

PITTS: I would like to see multispectral scanner band 7 split into two parts to avoid the major water absorption at 1.14 and 0.94 micrometers. You can still perform remote sensing in the two clear regions. You just narrow the bands and divide them into two parts. Based on your work, would you conclude that bands 5 and 6 are sufficient to obtain your ratios of 0.68 to 0.78 micrometers, or would you need new and narrower bands?

SMITH I cannot specifically answer your question. We have only attempted narrow wavelength bandpasses primarily in a field situation. However, this problem is presently being studied.

PARK: The issue of the ERTS bands has been extensively examined. You can center the bands approximately where you want them; however, at that altitude and speed, you cannot narrow the bandwidth. Because of the energies involved and the desire to produce good radiometric and pictorial data, each band has six different detectors that are

multiplexed to produce the energy for each broadband. The center of the bandpass can be changed to optimize it for a variety of conditions. Devices are being developed in the photodiode and charge-coupled device field that have efficiencies much greater than the present metal detectors. Within approximately 5 to 10 years, technology will be available to lighten the optics, narrow the bandwidth, and accomplish a variety of things. Presently, we are fairly constrained to a 100-nanometer bandpass.

$$\rho = 0.028 + 0.1e^{-0.004 \times chlorophyll}$$

R = 0.88
N = 112
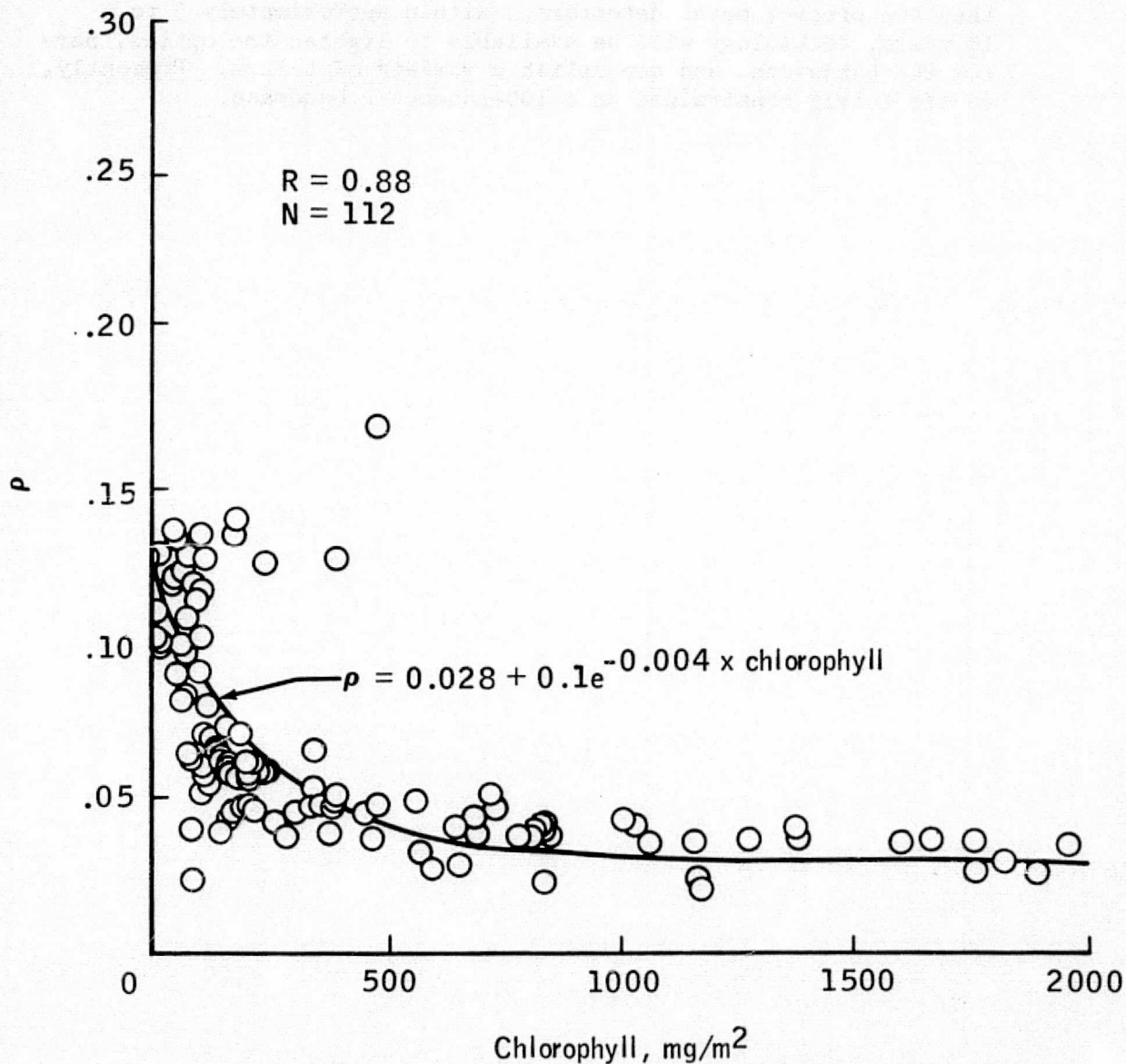
(a) Chlorophyll for ρ at a wavelength of 0.68 micrometer.

Figure 14-1.- Canopy reflectance of blue grama as a function of
variables, where R is the correlation coefficient, N is the
number of samples, and ρ is reflectance (ref. 14-1).

$P = 0.26 - 0.1e^{-0.004 \times \text{leaf water}}$

$R = 0.89$
$N = 112$
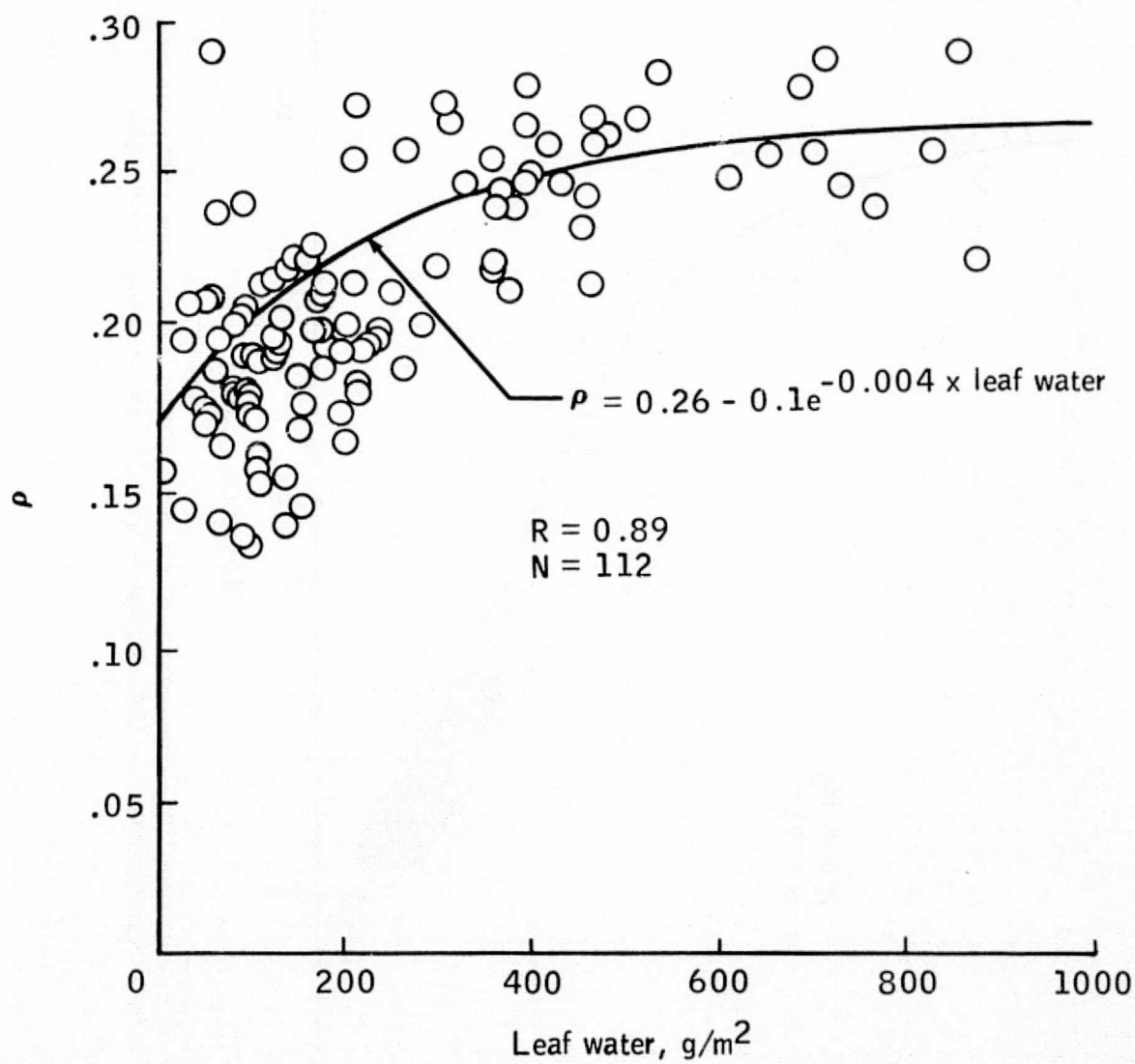
(b) Leaf water for ρ at a wavelength of 0.78 micrometer.

Figure 14-1.- Concluded.
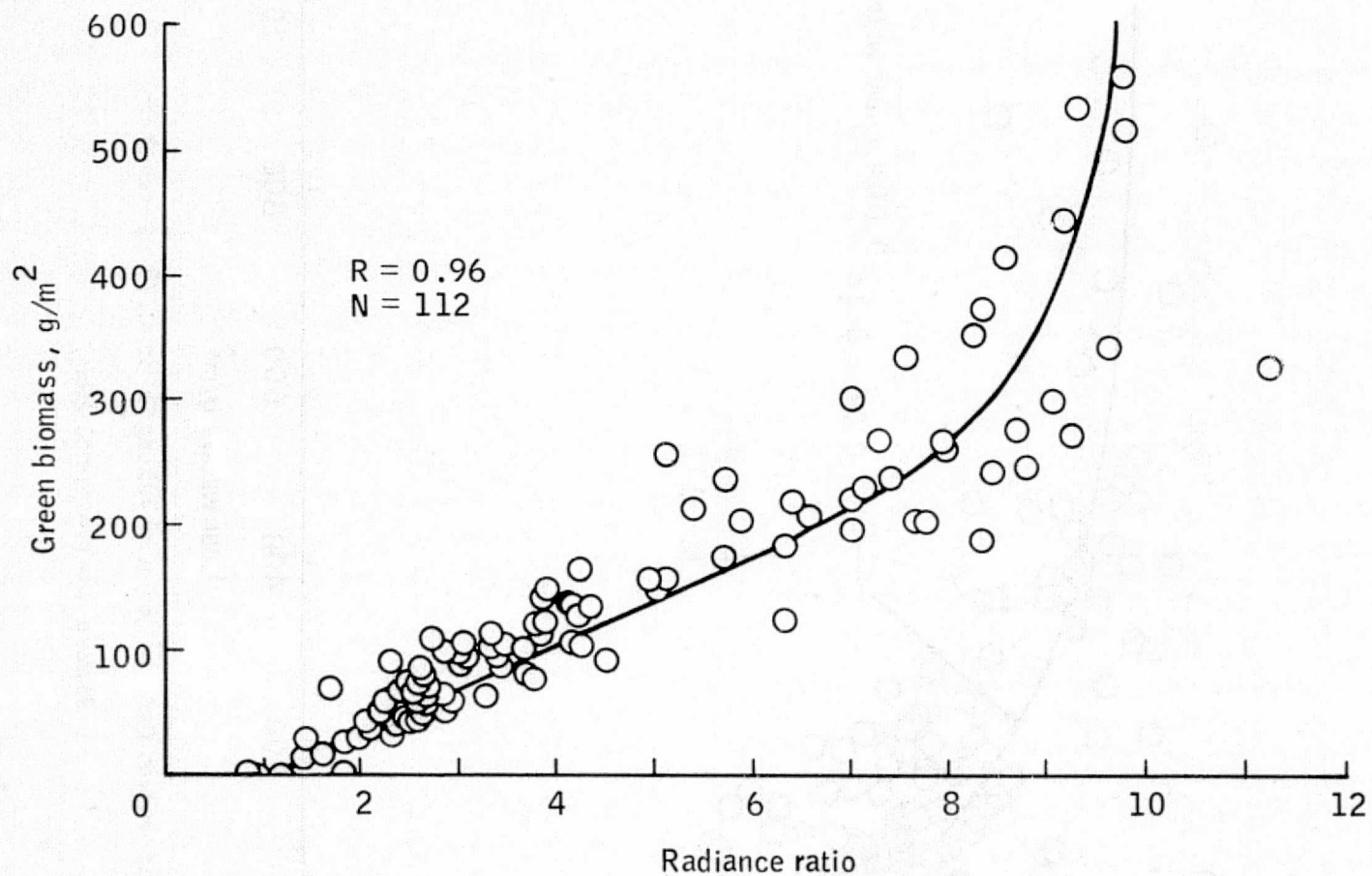
Figure 14-2.- Green biomass of blue grama plots as a function of the ratio of the radiance at 0.78 micrometer to the radiance at 0.68 micrometer (ref. 14-1).
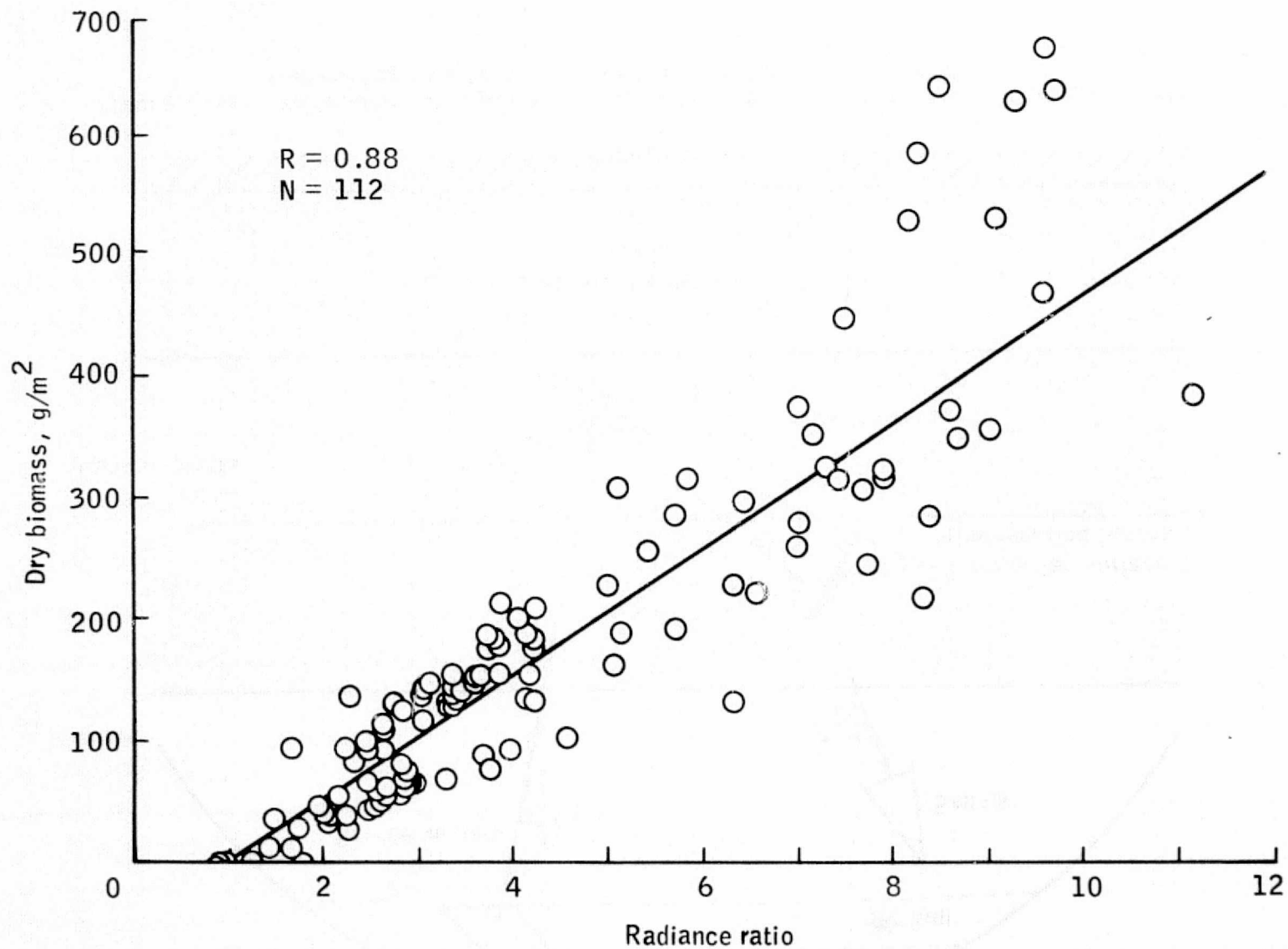
Figure 14-3.- Dry biomass of blue grama plots as a function of radiance ratio where dry biomass is equal to -46.8 + 50.8 × radiance ratio (ref. 14-1).
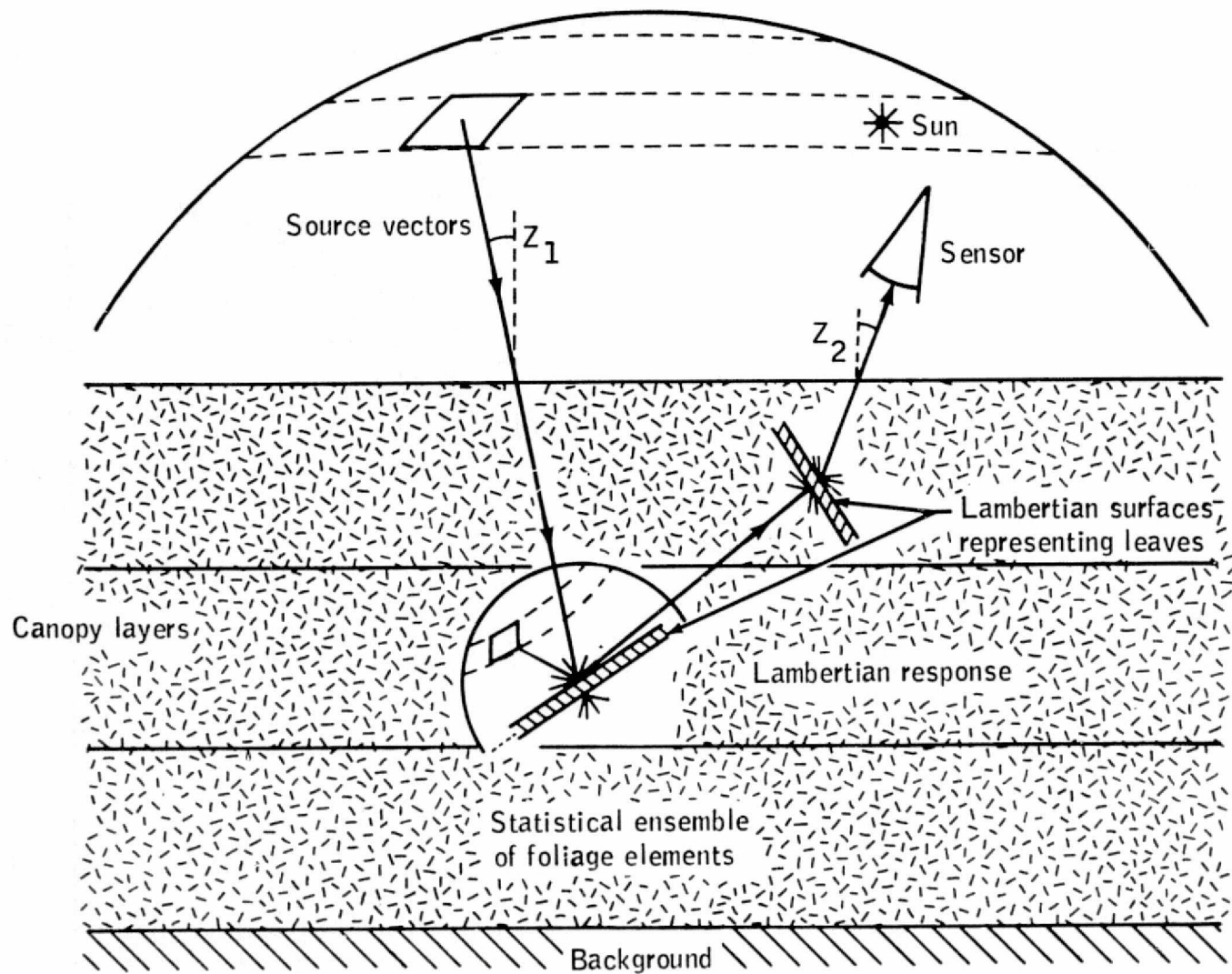
Figure 14-4.- Schematic of a plant canopy approximated by stratified foliage layers containing statistical ensembles of Lambertian surfaces.
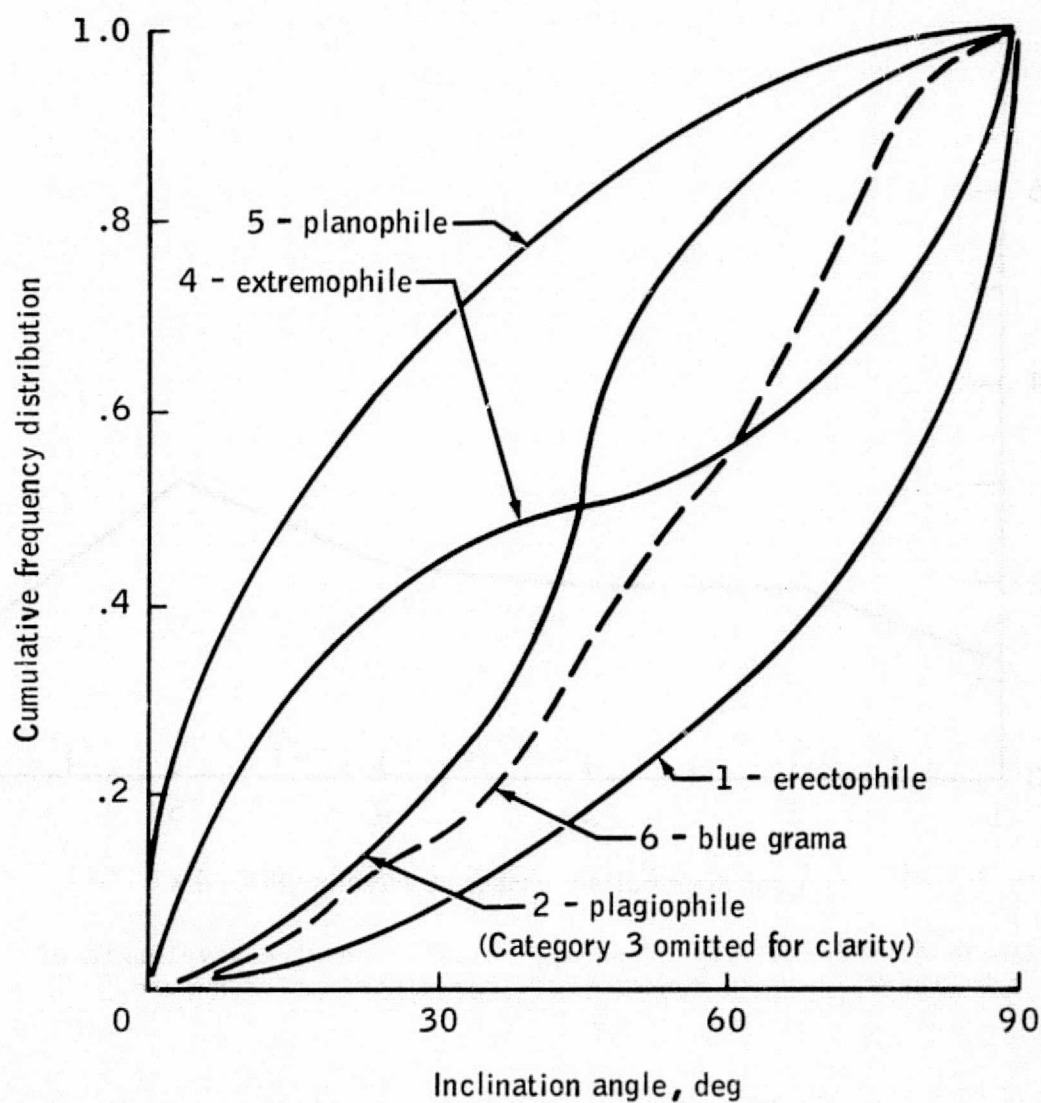
Figure 14-5.— Theoretical leaf distribution functions and measured distribution for blue grama (ref. 14-2).
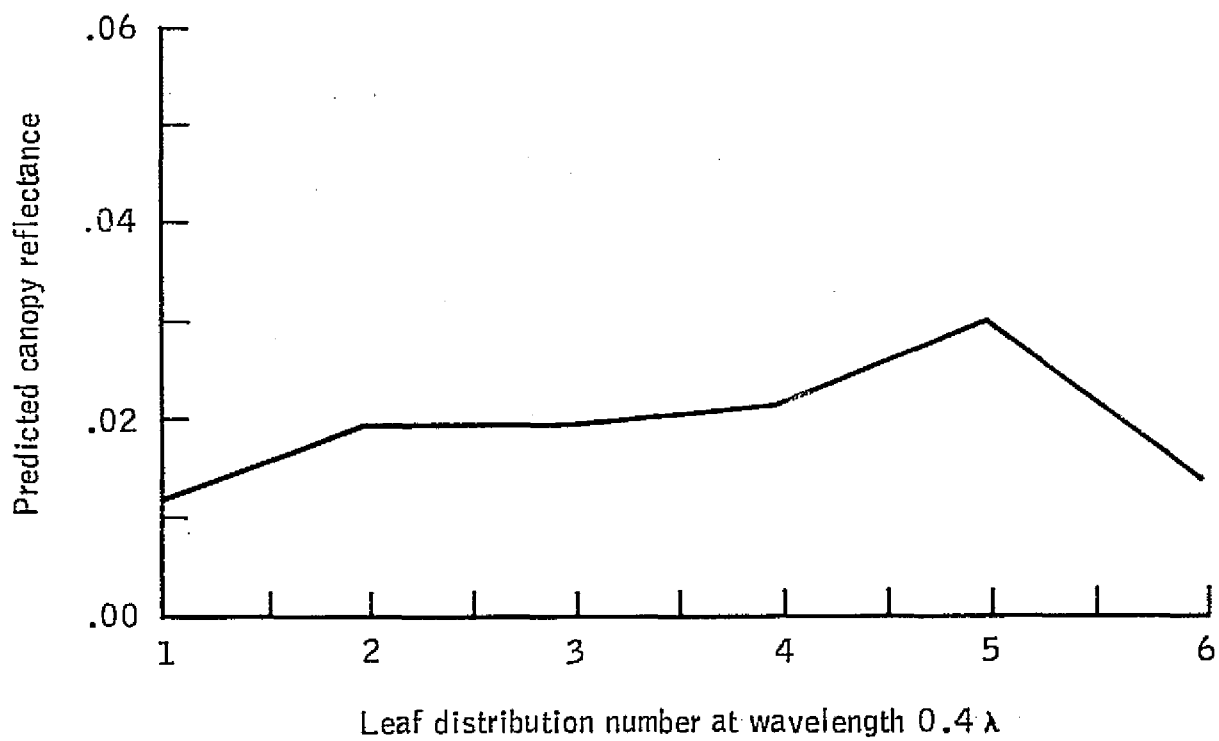
Figure 14-6.— Sensitivity of canopy reflectance at a wavelength of 0.4 micrometer as a function of leaf distribution number.
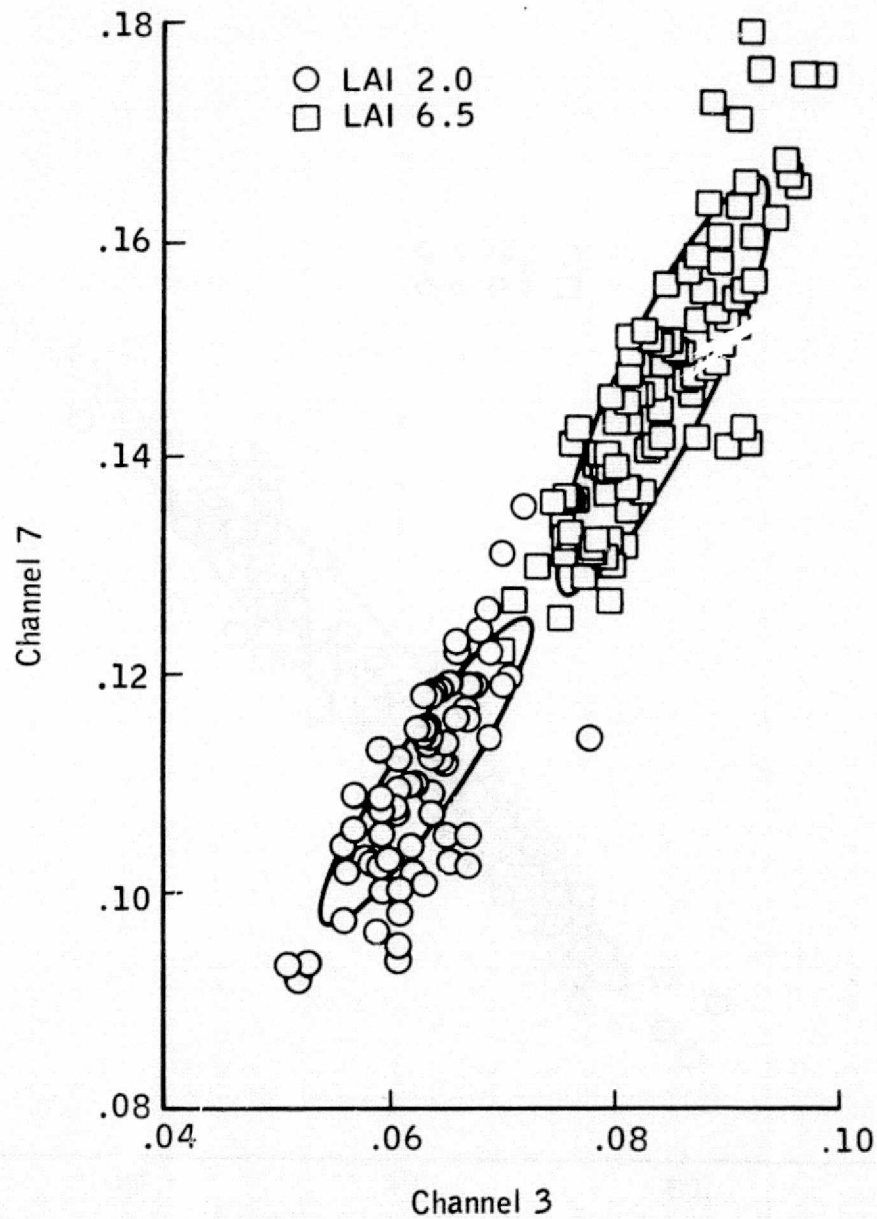
(a) Best scan angle at 65°.

Figure 14-7.- Spectral reflectance scatter plots for two LAI classes taken at a solar zenith angle of 44.5° (ref. 14-3).

O LAI 2.0
□ LAI 6.5
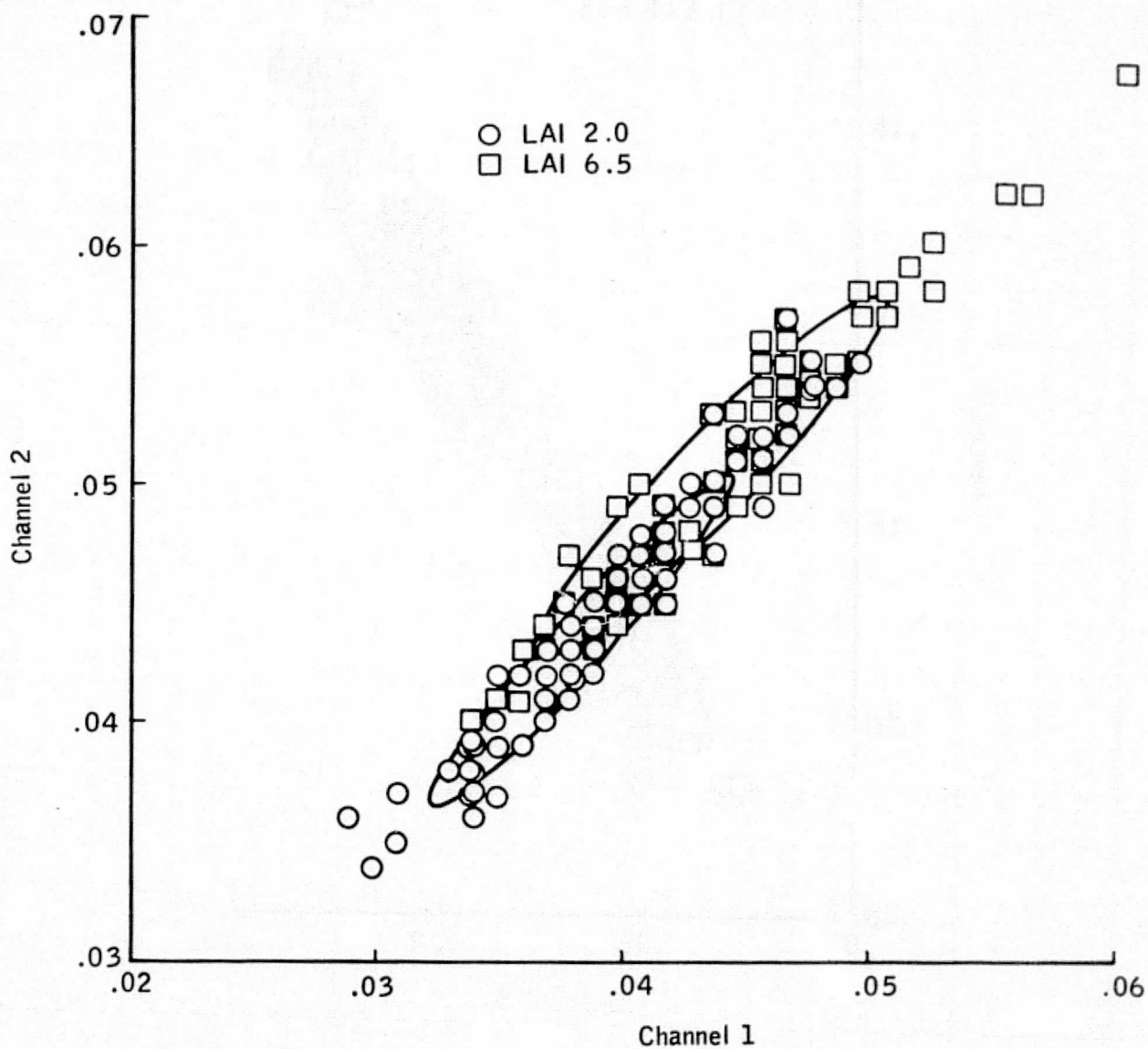
Channel 2

Channel 1

(b) Worst scan angle at 45°.

Figure 14-7.— Concluded.
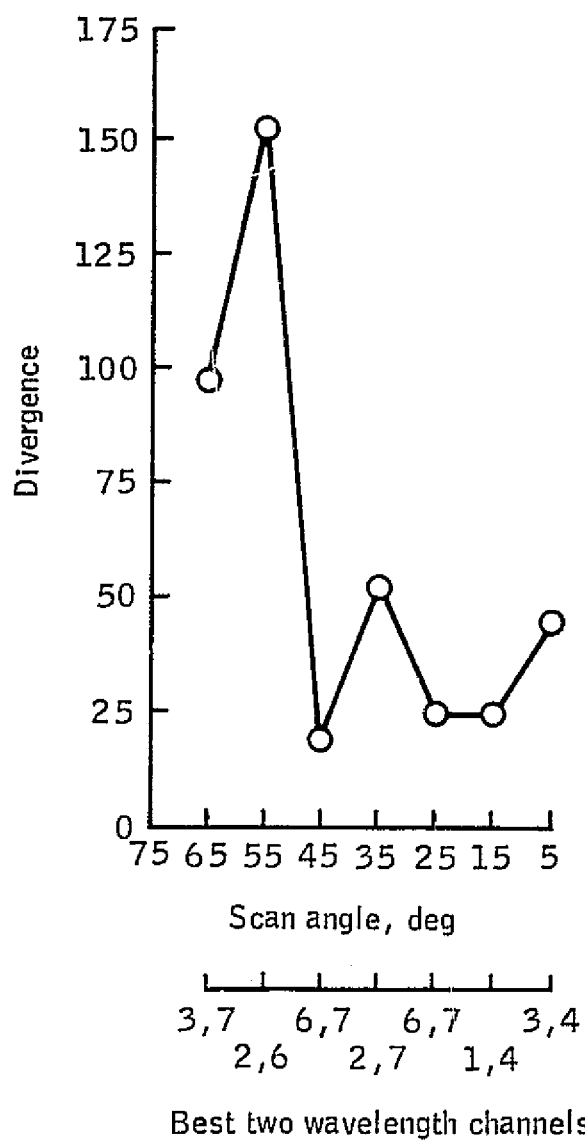
(a) Computer simulation at a solar zenith angle of 22.3°.

Figure 14-8.- Variation in maximum divergence with scan angle
for the best two wavelength channels (ref. 14-3).

Best two wavelength channels
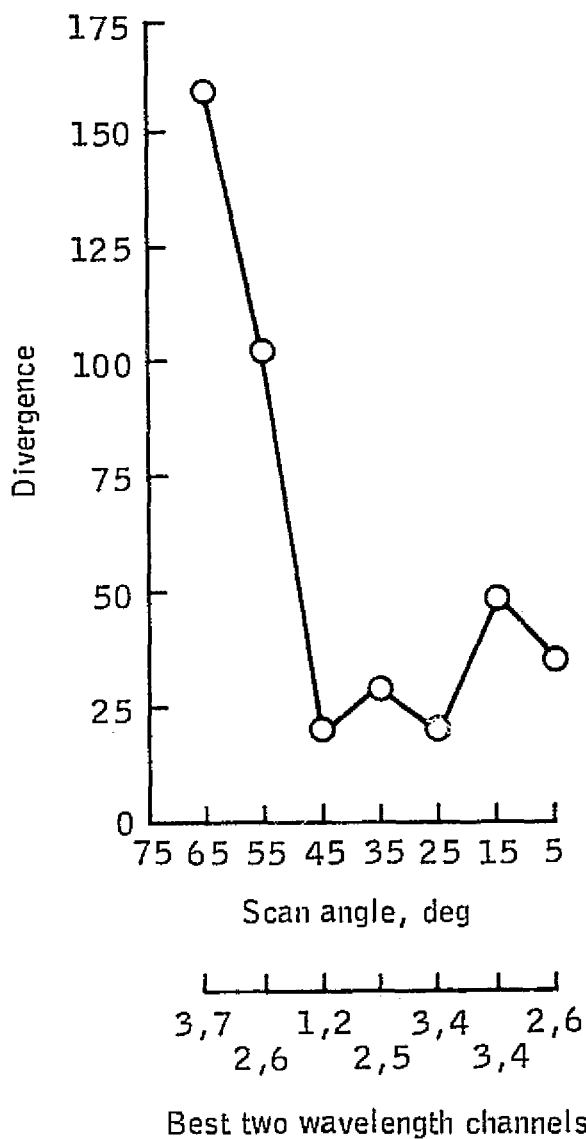
(b) Computer simulation at a solar zenith angle of 44.5°.

Figure 14-8.- Concluded.

15. MODELING THE INTERACTION OF METEOROLOGICAL VARIABLES

AND LEAF AREA INDEX ON YIELD

By Gwynn Suits*

The central issue of this conference is to achieve, by some economic and timely method, an estimation of wheat production over a large area. Because some methods are politically unacceptable, uneconomical, or unfeasible, the remote-sensing technique is the most suitable. To amortize the cost of satellite technology with remote sensing is very economical. Thus, satellite remote sensing presently surpasses all other methods. However, satellite remote sensing is applicable only to objects that are in the line of sight of the communication link. Remote sensors transmit to an object on the ground by using electromagnetic radiation. Therefore, the objective is to untangle the meaning of this communication.

A canopy model is a deterministic model using a radiation link from the Sun to the ground to the satellite. Incident radiation mixes with ground radiation and canopy radiation and is reflected back to the sensor where it is recorded. Use of a deterministic model can relate the structure on the ground, the radiation of the structure, and the spectral properties of the structural components to the resulting signal from the satellite. Atmospheric distortion of this communication can be accounted for to some degree. In addition, a photogrammetric mapping capability can establish the canopy areas that are being detected. The relationship of area and structure to yield or forecast of yield is the major problem. A mathematical deterministic model for agricultural crop pnenology and yield estimates has been initiated to complete that relationship.

A highly nonlinear system is apparent in an agricultural crop. The structure of this nonlinear system can be remotely detected at different times throughout its growing season. The question arises whether to become involved with the physiological inner workings of the canopy or to take the gross and over statistical approach. The canopy model is the result of a highly nonlinear, complex system, and researchers are not accustomed to handling this type system. The output of the nonlinear system is not proportional when an environmental factor is changed. The plant canopy contains a saturating photosynthetic action. Stomates open and close for many different reasons. Both nonlinear moisture flow and hysteresis of moisture flow occur in soils. In addition to being nonlinear, the canopy model is also subject to nonholonomic constraints. Plant growth is also nonlinear and subject to nonholonomic

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constraints. To isolate the influence of separate variables when every other variable is involved in some unknown way is very difficult.

A deterministic model is favorable because it contains the characteristics of a nonlinear system. A nonlinear system is characterized by its function (eqs. (15-1) and (15-2)). A system response occurs at some time. This response R could be a growth factor.

$$R = R(G1, G2, \ldots GK, X1, XZ, \ldots XN) \qquad (15\text{-}1)$$

or in differential form

$$dR = \frac{\partial R}{\partial X1} \Delta X1 + \frac{\partial R}{\partial X2} \Delta X2 + \ldots + \frac{\partial R}{\partial XN} \Delta XN \qquad (15\text{-}2)$$

where G is a genetic parameter and X is an environmental variable. Thus, R will be a function of different possible environmental variables X. In a nonlinear system, if the values of one or two of these variables are altered, then one, two, or possibly three of these variables represent the dominant factors for changing this response. However, if a slightly different combination of altered values occurs, then the response will be governed primarily by two or three other variables rather than by the previous ones. Occasionally, when saturation occurs, other factors start controlling the responses, and changes in the original variables become ineffective. Such response behavior is peculiar to nonlinear systems. This effect can be illustrated by forming the differential of the response. The partial derivative of the response is obtained with respect to each variable multiplied by the differential of each variable. When one of these variables is dominant, the partial derivative with respect to that variable is the large one. These partial derivatives for changes in other variables that are very insensitive will be small. In a certain restricted range of variable values, the system appears almost linear. However, any function is linear if a small enough interval is used.

Where these systems are linear in these small ranges, the statistical linear-regression approach works very well. The problem is that the range of these variables is too large; thus, when these variables go to another region in which other variables are dominant, application of the statistical approach to the first variables fails badly. Statistical approaches can work well over certain limited regions, but they can fail when disaster strikes. A small range can be represented by a linear regression even though a highly nonlinear formula is used. The major objective is to replace this differential relation with a deterministic formula for obtaining the response. Certain parameters A, B, and C are presumed to be constant and are characteristic of the phenomenon. If this formula could be derived, statistics would be unnecessary. This formula can be created, and then the values of A, B, and C that are best fitted by statistics can be established later. If these parameters are constant or nearly constant for the phenomenon, then they should not vary greatly; therefore,

the fitting for differential analysis to real response data would be the exact purpose of statistics — that is, to best fit a deterministic model with indeterminate parameters, which are to represent constants of the phenomenon. These constants of the phenomenon should correspond to those items that are genetically determined. Therefore, a mathematical model should be developed that is based as closely as possible on the basic functions of the plant organs, which can be identified with or closely tied to the genetic properties of that plant. If this task has been accomplished, the undetermined parameters of the relationship presumably will be slowly varying, if not constant. Even though undetermined parameters will exist, these parameters will represent properties that should be constant. The remaining environmental variables should result in peculiar nonlinear behavior as a result of their wide-ranging action.

The proposed model must be connected with the structure to be used for the communication link. That is, if a model is formulated without consideration of structure, a break is left in the link. A link from sensor to structure and a link from structure to yield is necessary.

In beginning the derivation of the response function, a photosynthetic model was used for the single isolated leaf and was placed into a canopy model containing depth, orientation, plant density, and so forth. Important environmental influences were applied hourly, and the phenology of this hypothetical plant was calculated. The top part of the canopy model was emphasized, whereas plant roots were ignored. Therefore, transpiration, which is obviously an important element of this model, could not be measured. This deterministic model, run with some hypothetical data, has been encoded in computer form. The computer simulation is shown as a function of the day of year (fig. 15-1). The simulated weather of Dodge City, Kansas, was generated by a pseudorandom number so that the long-term weather statistics of the computer matched almanac averages for Dodge City. The producing leaf area index (LAI) and the fixed carbon dioxide (CO_2) yield in moles per square meter are shown. The translocation scheme in this selected species results in leaf shedding or leaf necrosis as leaf and stem vacuole storage is depleted. Unless unusual weather conditions are encountered, the shape and timing of the LAI and yield responses are controlled largely by the values of the genetic parameters.

The next step is to introduce the substructure of the canopy model and to incorporate the parameters that are strictly genetically controlled. Morphology will have to be incorporated into the canopy model, with precise specification of manner and time of occurrence. Some of the genetically controlled parameters may be available in literature. If these parameters are not available, this canopy model will have to be calibrated by statistical means.

QUESTIONS AND ANSWERS

HARTLEY: To identify statistical approaches with the fitting of laws linear in the input X variables is not correct. Nonlinear refers to the parameters A, B, and C that we are fitting. However, the statistical approach can use models that are not only nonlinear in the original input X variables but also nonlinear in the parameters. To discuss whether this model is deterministic or statistical is not productive because a deterministic model is a special case of the statistical model; thus, the statistical model is a more general concept.

SUITS: Yes, I think a misunderstanding of terms exists. The deterministic model is nothing more than the limit of realistic statistical models. Thus, the statistical model is distinguished from the deterministic model by degree. We use the overt approach — ignoring all of the physiological information that we have. For example, in this canopy model the conservation of energy and matter are strictly adhered to. No carbon dioxide may enter and then suddenly disappear. The amount of available radiation must be accounted for, and it must go somewhere. Therefore, to ignore these fundamental laws and to juggle the curve fitting would result in what I refer to as a statistical model.

HAUN: Phenology is defined as the science of periodic phenomena, which means flowering, fruiting, or things that happen at nonlinear or nonuniform periods throughout the life of a plant. A better evaluation of plant existence is that of quantitative morphology. Another point of interest is this characterization of different kinds of models. I think the big contrast is between deterministic and stochastic models. Much time will elapse before we make a stochastic model of plant growth. As far as the deterministic models are concerned, if we use this quantitative morphology of plant development, we now have a dependent variable that we can study as an influence of environment. With the advent of the computer, no statistical limitations exist. Having too many variables is not possible. The curvilinear or nonlinear nature of the variables is not too much to manage. If we use the correct dependent variable and statistical procedures, I think we can discover most of the facts that we need to know.

SUITS: I agree with this viewpoint that the complexity of the model is immaterial with the advent of modern computers. Cogency must be preserved rather than the effort to calculate the final result. We are less constrained with modelmaking now that we have the ability to test congency on the computer. I do believe that your quantitative morphology is an important influence on any further modeling. A stable model is one that will not fall apart when a slight change occurs.

TRACY: The relationship between the photosynthetic models and the canopy
         models was not clear. I do not understand the relationship between
         those kinds of models and remote sensing.

SUITS: Well, I omitted much of that information. If we can know the
         physical structure of the canopy model, we can predict with good
         reliability the signal we will get. What remains to be done is to
         note what the biological structure means economically for yield.

SMITH: We have both a curse and a benefit in this mechanistic deterministic
         modeling. The benefit is that the more information we want to
         extract from the model, the more we have a physical basis for doing
         that. The curse is that we are limited by the least identifiable
         parameter. For example, on your hourly determination of the LAI
         development, many parameters are involved. Some parameters are
         known; some are not well known; and some probably are not known on
         an hourly basis. Because of limited data availability, we are in
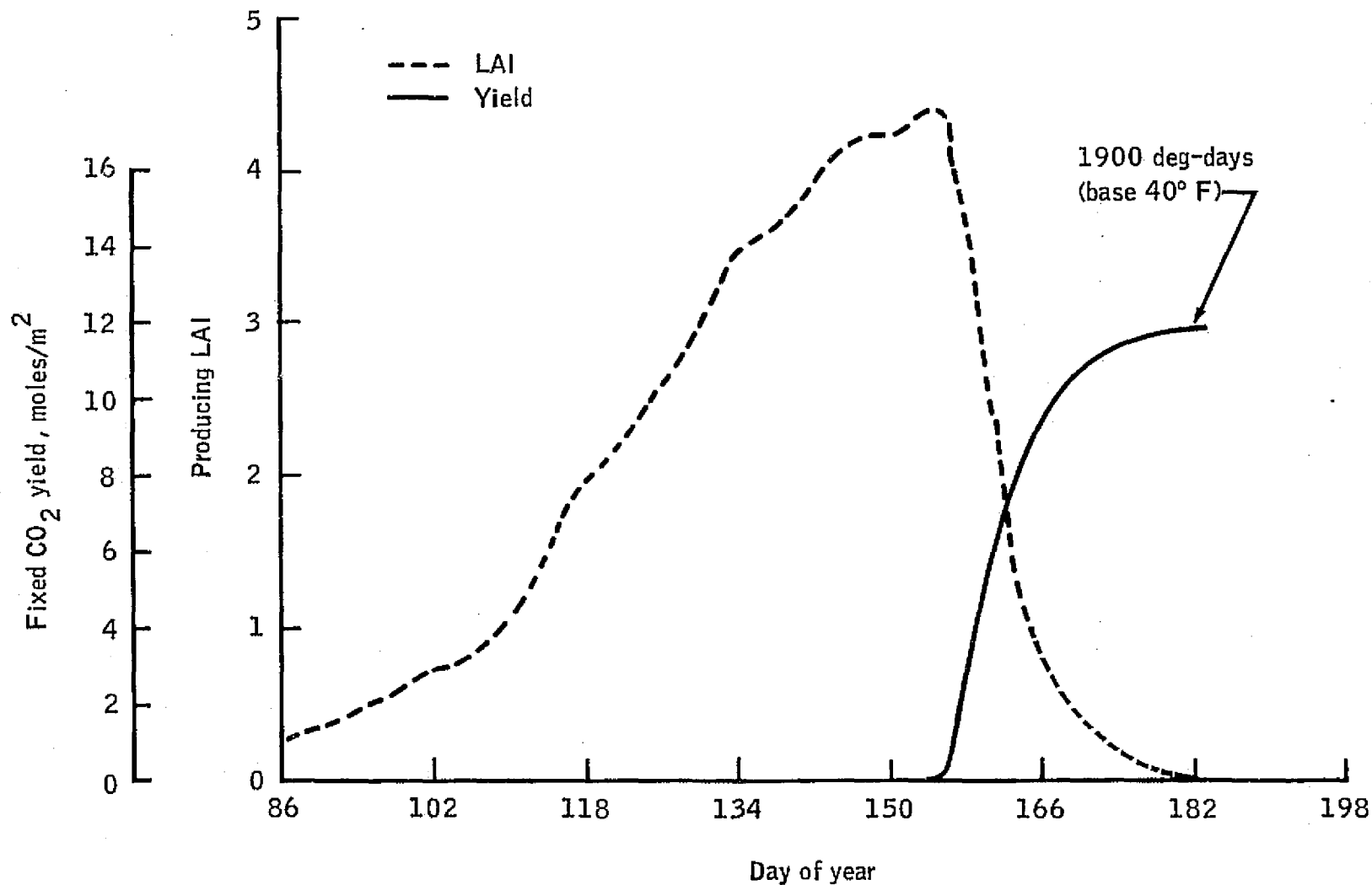   danger of creating a complicated process.

Figure 15-1.- Plot of fixed CO_2 yield and producing LAI as a function of the day of year derived from computer simulation.

16. APPLICATION OF REMOTE SENSING

TO THE ESTIMATION OF EVAPOTRANSPIRATION

By Blaine L. Blad*

Five basic environmental factors affect photosynthesis or crop yield: the level of soil nutrients, the solar radiation intensity and distribution in the canopy, the crop temperature, the carbon dioxide concentration in the canopy, and the water availability to the leaves. The particular project reported here is concerned with aspects of two of these factors: crop temperature and water availability, particularly as it relates to evapotranspiration (ET) rates.

Nebraska has hot, dry winds, primarily from the southwest, that bring large quantities of sensible heat into the region. This sensible heat is consumed in ET; as a result, many of the traditional climatic ET models do not seem to work very well. Therefore, other approaches of estimating ET have been studied. If the modified crop resistance model is successful, it can be used to estimate ET on a large-area basis rather than just the single-field or point measurement provided by micrometeorological methods.

For the past year, the University of Nebraska has been developing a model to predict crop water use based on crop temperature and other available meteorological parameters such as radiation, wind, humidity, temperature, and so forth. Eventually, remotely sensed thermal imagery will supply data on crop temperatures. Aircraft and satellites can then supply information for water-use estimation of crops covering a very large area. The first of these approaches is by using a mass transfer-type equation such as

$$LE = f(u)(e_s - e_a) \qquad (16-1)$$

where LE is the latent heat flux, $f(u)$ is a function of the windspeed, e_s is the saturation vapor pressure, and e_a is the vapor pressure at a given height. This approach has been used successfully in estimating the evaporation from large water bodies and is currently being used in the Great Lakes region. Recent results of the studies suggest that this approach can be used successfully to estimate ET rates from subirrigated alfalfa.

The model primarily being used is a modification of the crop resistance model by Brown and Rosenberg (ref. 16-1). This model is

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$$LE = C_p\rho(Ta - Tc)/r_a + (Rn + S) \qquad (16\text{-}2)$$

where LE is the latent heat flux, C_p is the specific heat of air at constant pressure, ρ is the density of air, Ta is the air temperature at a given height, Tc is the crop temperature, r_a is the boundary layer resistance, Rn is the net radiation, and S is the soil heat flux. The parameter r_a is a function of the windspeed and aerodynamic roughness of the crop. Also, LE is directly proportional to a term combining net radiation and soil heat flux. When crop cover is complete, the soil heat flux is negligibly small. This model is being tested to determine its applicability to estimate evaporation from large areas and to determine the feasibility of using the remotely sensed thermal imagery for supplying crop temperatures.

This model was tested in 1972 and 1973 at two different sites in Nebraska. One site was in the Platte River Valley in the east-central part of the state near Columbus, and the other site was in the Platte River Valley in the central part of the state near Cozad/North Platte. Permanent experimental laboratories, located at Mead and Scottsbluff, have micrometeorological stations containing lysimeters. The University of Nebraska is cooperating with Kansas State University to conduct similar studies in 1974 at these two stations and at one located near Manhattan, Kansas. Thus, the resistance model will be applied over a fairly large region and will examine ET from several different crops.

The results of the research thus far are primarily qualitative. Under advective conditions (heat transfer from air to crop), when the crop temperature is cooler, the water use will be greater (eq. (16-2)). A portion of a thermal scan at the research site near Columbus was made under advective conditions on June 1, 1972 (fig. 16-1). Several interesting, qualitative relationships can be seen in the thermal scan. Lighter areas are an indication of cooler temperatures. A difference of approximately $10°$ to $12°$ C exists between the darkest and lightest areas. Alfalfa, depicted in area c, is a crop that offers very little resistance to the flow of water vapor; therefore, it transpires at near-potential rates as long as it has water available. The light color of the thermal scan suggests that ET rates are relatively high in this field. Adjacent to the alfalfa field is a pasture (area a). Past work indicates that in the Nebraska environment a pasture will use approximately 20 to 25 percent less water than alfalfa; thus, the temperature of the pasture should be slightly warmer as verified by the thermal scan. Area b, a recently plowed bare field, was considerably warmer; thus, evaporation rates were much lower. The light color of area d indicates that wheat at this growth stage is probably using about as much water as the alfalfa. Area e shows fields that were bare at this time but were later planted with corn. Left of area a is a farmstead. The windbreak around the farmstead is clearly visible, and the thermal scan shows that the trees are cool, which suggests that the trees were probably transpiring at a high rate, although no measurements of ET from the trees were made.

Taken on August 16, 1972, the second thermal scan (fig. 16-2) is for the same area. Unfortunately, the thermal scan is quite poor. Area c, the alfalfa field, again appears light. Area b, which was dark in figure 16-1, now appears quite light because it had been planted with soybeans that were fully developed at this time. The wheat in area d had been harvested; the area appears dark, indicating that temperatures are quite high and evaporation rates are relatively low. Except for two bare strips, the field in areas e and f had been planted with corn. Again, the windbreaks are visible to the right of area a. Also, the pasture (area a) is still warmer than the alfalfa.

These thermal scans were taken by the U.S. Geological Survey. Numerous problems have occurred with aircraft and scanners, and unfavorable weather conditions ensued during scheduled flight periods. Considerable beneficial ground-truth data exist, but very little beneficial remotely sensed thermal imagery is available.

The Nebraska National Guard, headquartered at Lincoln, recently acquired equipment for taking thermal scans; however, scheduling them for missions to obtain thermal imagery is difficult. A thermal scan was taken in the area near Cozad on August 28, 1973 (fig. 16-3). Advective conditions prevailed at the time of the flight. The area near Cozad is particularly suited for thermal scans because it is an area dominated by alfalfa and corn. Research was conducted in an alfalfa field (area b) and an adjacent cornfield (area c). Area a, a recently planted alfalfa field, appears as essentially bare surface. The corn, based on ground measurements, is approximately 2° C warmer than the alfalfa field and appears slightly darker in the thermal scan.

Some areas in the alfalfa field appear dark. The two largest dark areas are large haystacks. Other dark areas are places where the crop was probably under severe moisture stress or where patches of bare ground existed. The detection of these stressed areas suggests that thermal imagery can be an important factor in indicating crops that are under stress from insufficient water, crop disease, and so forth. Stressed areas would be visible on the thermal scan because of differences in temperature between the stressed and nonstressed vegetation.

To use the crop resistance model for estimating ET, constants must be determined from ground measurements. A Barnes infrared (IR) thermometer was used to obtain measurements of crop temperature from a height of approximately 2 meters. The Barnes IR thermometer was used for two summers to obtain crop temperature data needed to calibrate the crop resistance model against the Bowen ratio-energy balance model. The Bowen ratio-energy balance model, using micrometeorological data for estimating ET, has been calibrated against lysimeters to make reliable estimates of ET for periods as brief as 15 to 30 minutes (ref. 16-2). The imagery obtained will be analyzed in more detail, and additional imagery will be obtained to determine the feasibility of obtaining crop temperatures from thermal scans. The Barnes thermal radiometer can also serve as ground truth (surface observation) for the thermal imagery by giving the temperature of a particular field.

The research has two major objectives. One objective is to develop models for the estimation of ET for large regions by using crop-temperature data in conjunction with available meteorological parameters. The second objective is to determine the feasibility of using thermal imagery to obtain crop temperatures. On the basis of results obtained thus far, these objectives should be achievable. Thermal imagery may also be useful for determining whether or not fields of wheat and other crops are under moisture stress.

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16-2. Blad, B. L.; and Rosenberg, N. J.: Lysimetric Calibration of the Bowen Ratio-Energy Balance Method for Evapotranspiration Estimation in the Central Great Plains. J. Appl. Meteorol., vol. 13, Mar. 1974, pp. 227-236.

QUESTIONS AND ANSWERS

JONES: Could you state the altitudes from which the thermal scans were run?

BLAD: The first and second flights were obtained from approximately 4000 feet; the third flight, from approximately 3000 feet. We will probably go to lower elevations, approximately 2000 to 3000 feet, for our work next summer. Most satellites have not had thermal scanners on them, or the resolution has been insufficient to provide the temperature accuracy required by the model. The remote-sensing technology we need is in the future. Our present objective is to determine a feasible method for estimating ET.

PITTS: I am interested to know if land use — that is, how much wheat you plant in any given year — affects meteorological conditions in the Great Plains. Do you have any published results?

BLAD: No. We are still working on the publication of our findings. We have some preliminary results, but they probably will not be published for a few years.

Figure 16-1.- Thermal imagery of the research area near Columbus, Nebraska, taken during the afternoon of June 1, 1972, from approximately 4000 feet. Area a is a pasture; areas b and e are bare fields; area c is an alfalfa field; and area d is a wheatfield.
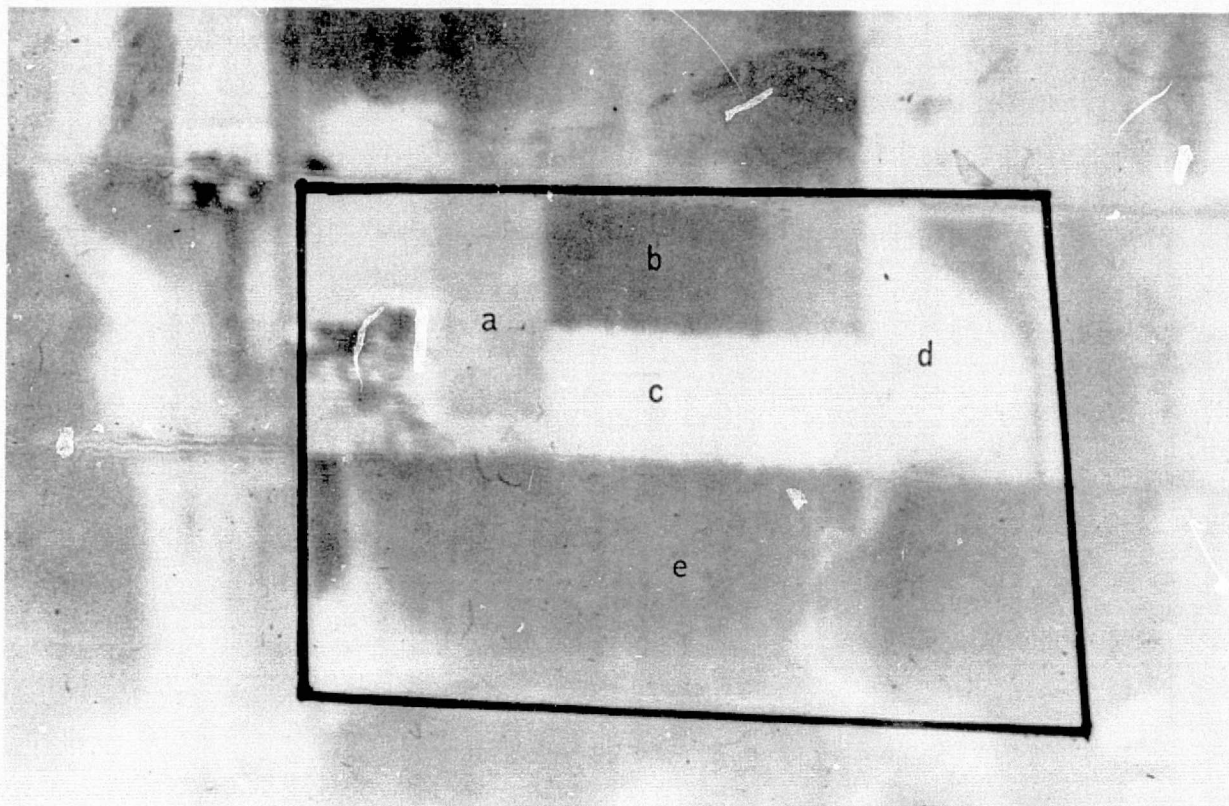
Figure 16-2.- Thermal imagery of the research area near Columbus, Nebraska, taken during the afternoon of August 16, 1972, from approximately 4000 feet. Area a is a pasture; areas b, d, and f are bare fields; area c is an alfalfa field; and area e is a cornfield.
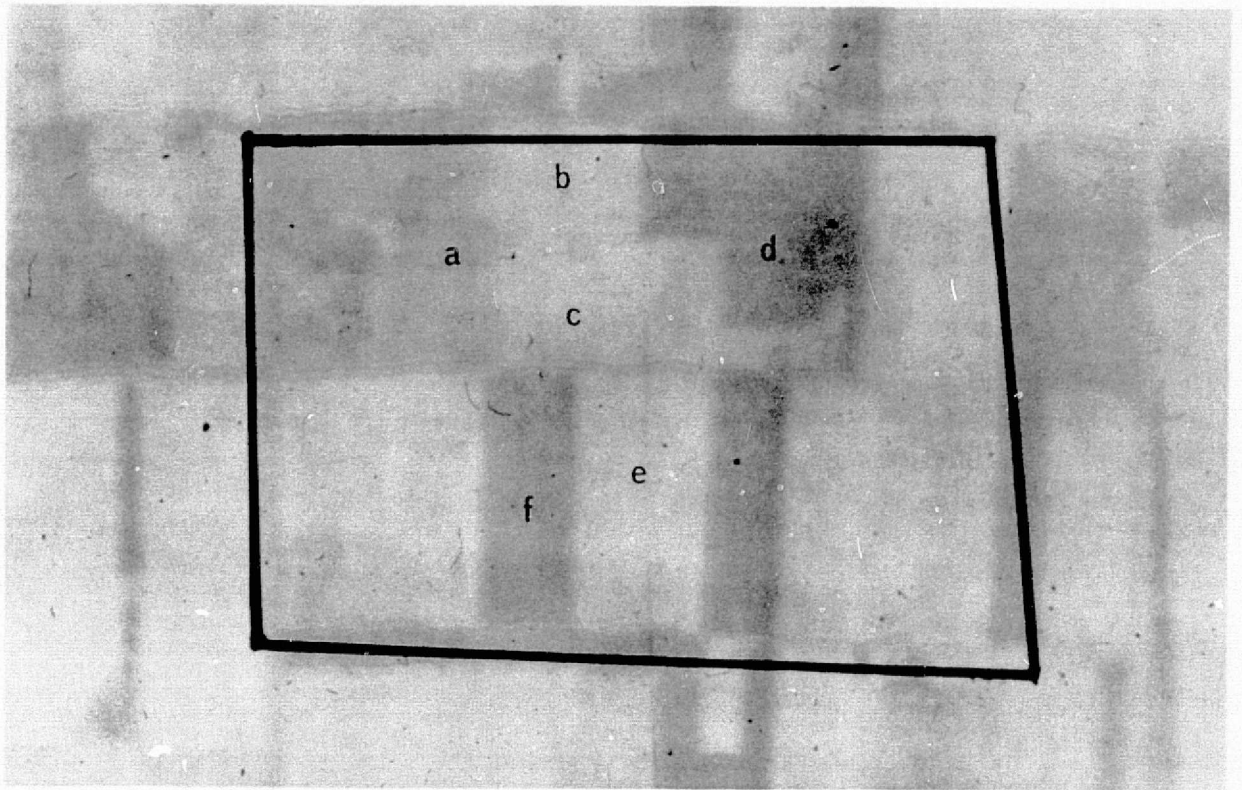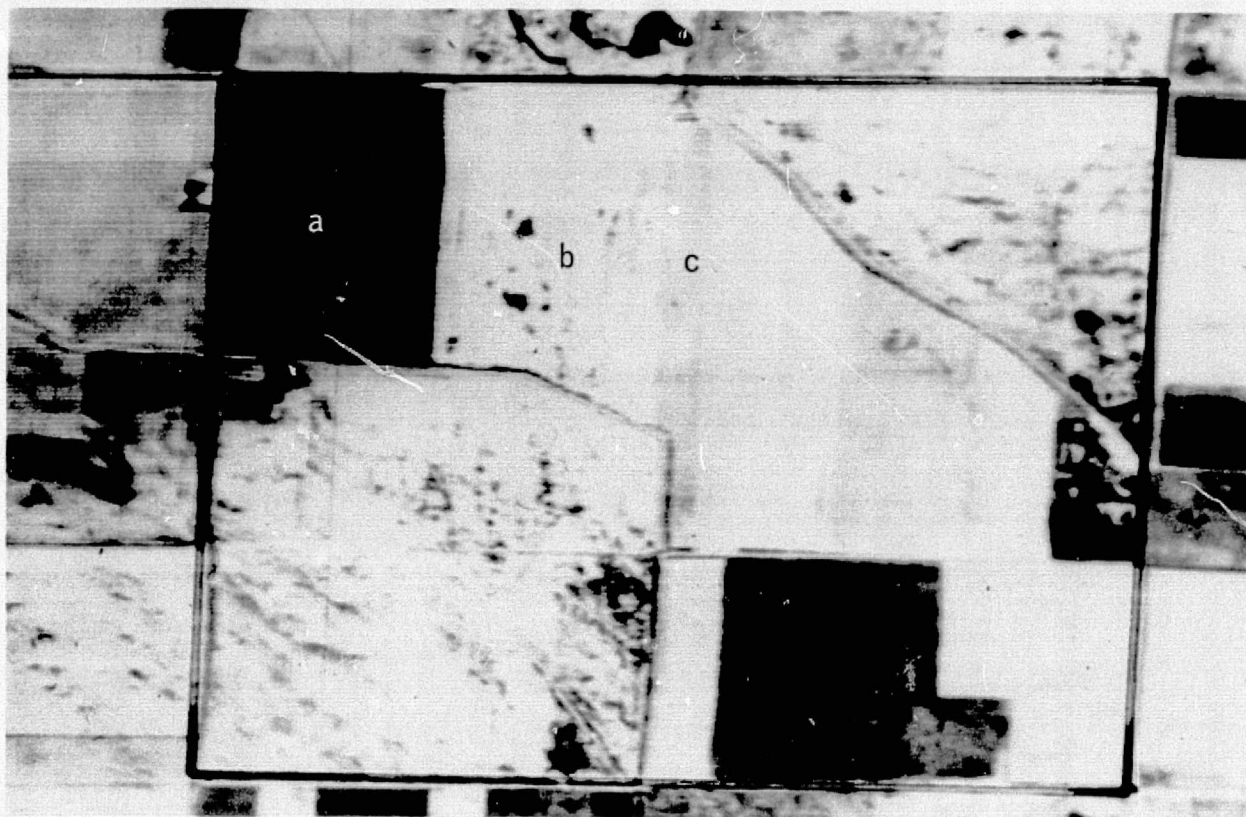
Figure 16-3.- Thermal imagery of the research area near Cozad, Nebraska, taken on August 28, 1973, from approximately 3000 feet. Area a is a recently planted alfalfa field; area b is an alfalfa field; and area c is an irrigated cornfield.

17. MODELING CORN GROWTH BY INCORPORATING SOIL AND CLIMATE FACTORS

By Dwain Horrocks[*]

In 1969, Illinois began experimenting to determine what effect the soil moisture or the soil water–holding capacity would have on corn yields. One plot was located 160 kilometers north of Urbana; another plot was located at Urbana; and two plots, approximately 2 kilometers apart, were located near Effingham. The plots within the soil types contained from 30 to 120 centimeters of rooting depth. These soils were loessal deposits over glacial till. The northern soil sites were composed of calcareous glacial tills. The zone underneath these soils was impervious to root growth. The southern soils sites contained a matrix layer that was also impervious to root growth. For each site, six different plot areas were chosen and were replicated four times. In these areas, the low-growing corn would appear where the soil is fairly shallow, and the tall-growing corn would appear where enough soil exists to supply an adequate rooting zone.

Plots were planted in cornfields owned by various farmers. Samples were taken weekly for a 10-week period — that is, 6 weeks before tasseling and 4 weeks following tasseling. This had previously been determined to be the time when environmental alteration of corn yields occurs. Sampling included measuring the available water in a core at each site. Also, the available water–holding capacity of the root zone was measured at one time during the season. The regression model considered soil rooting depth, accumulated rainfall, maximum temperatures, and their interactions. Approximately 81 percent of the variability was accounted for in the regression model. Without the water–holding capacity of the soil or the rooting depth, most equations developed gave essentially the same answer — that is, approximately 55 percent of the variability was in the rainfall and temperature data. The model was quite sensitive because of the relationship between temperature/rainfall and planting dates.

Because the yield response to these various factors was well understood, this model was applied to a wider area. Sites in Illinois, Missouri, Kansas, Nebraska, and Iowa for which weather data were available were selected. Yields were then calculated. April 8 represented the planting date, and pollination occurred on June 24. The April 8 planting date for the northwestern Iowa site is not realistic; therefore, these data would not be comparable to data obtained from a southern site such as Springfield, Missouri. An April 24 planting date is more realistic for the southern sites; however, for the southern parts of Missouri and Illinois, this date is a little late. Lack of moisture affected the estimated yield for southern Missouri, whereas data for the northern sites were fairly realistic.

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Planting date and location do affect corn yields. For April 8 in southern Missouri, which had an estimated 12 inches of available soil moisture in the rooting zone, the estimated yield was 132 bushels. In central Missouri, April 8 is a very early planting date; however, by April 28, corn should have been planted. In central Missouri, which had an estimated 12 inches of water available in the rooting zone, the estimated yield was 13. bushels. When an estimated 8 inches of water was available in the rooting zone, the estimated yield dropped to 120 bushels. With an estimated 4 inches of available soil moisture, the estimated yields dropped to 70 bushels. These yields are fairly realistic. With this type of available information, some fairly reliable estimates can be made of the effect of weather changes on corn yields. Furthermore, this same type of model could be developed for wheat or any other crop.

To estimate what would happen to corn yields as climate varies and to estimate the complete mid-West area, sites in Wisconsin, Minnesota, and Michigan should be considered. To accomplish this task, the general soil water-holding capacity and the production represented by a particular area must be determined, which would allow an estimate of the yield change that could occur as temperature and rainfall varied.

This study uses a deterministic model for estimating the yield or the growth of the corn plant. A parameter for soil water availability should be incorporated into the model. Also, the need exists to define some growth parameters in terms of the meteorological data and then relate this information to total yield.

A similar task was accomplished with corn yields in Missouri, Indiana, and Michigan from data collected over approximately 30 years. Excluding plant growth parameters, approximately 65 to 70 percent of the variability was accounted for in the regression equation by simple weather input parameters. However, as evapotranspiration, estimated from the environmental factors, was included, R^2 values up to 0.92 were obtained, which was a considerable improvement. The problem is that these equations cannot be used as a means of projection. However, they did account very well for what had happened.

QUESTIONS AND ANSWERS

PITTS: Could you tell me the form of your model?

HORROCKS: The form of the model was a regression analysis that included accumulated rainfall during a 10-week period. The model also included the maximum temperature of the soil involved and the interactions of the two effects. These interactions were checked for significance and added or deleted, depending on their significance.

PITTS: Are these effects additive or multiplicative, and are they linear or nonlinear?

HORROCKS: Some of the terms are additives, but one term has a multiplicative effect. When you say linear or nonlinear, I am not sure what you are discussing, but some squared terms are present. These terms are not curvilinear.

CHIN CHOY: What do you mean by availability in soil? How deep do you think your rooting depth was?

HORROCKS: Water-holding capacity was measured at a pressure of 15 bars. The rooting depth was estimated or measured from examining the core sample. The rooting depth was very easy to estimate on the soils that contained carbonated till under them; however, one of the matrix soils was a little more difficult to estimate.

NEWMAN: Was the evapotranspiration method used for water extraction?

HORROCKS: No term exists for extraction or evapotranspiration in the final prediction model.

ROBERTSON: Soil moisture lends itself very well to some type of an intuitive deterministic analysis. Dr. Baier and I have a model that we call a versatile soil moisture budget, which calculates soil moisture far better than anybody measures it.

HORROCKS: We have begun developing a computer program that enables us to keep a water balance throughout the season, and I think that we can do a very good job. We have not tested this program as far as plant and growth are concerned, but they will be tested eventually.

18. SUMMARY

PART A

By J. B. Peterson*

Obviously, the need for accurate crop prediction is necessary in many areas of the economy. However, accurate crop prediction is dependent on the technology of building models and systems analyses, the understanding of how to use the computer as a tool, and the technology of remote sensing. Thus, investigators from various disciplines have been learning these techniques and applying them to the problems of crop prediction. Obviously, a two-part job must be performed. One task is to predict immediately, using current technology, what is occurring in the world-commodity situation, and the second duty is to perfect a better system of predicting expected crop production on a large-area basis. A program including genetics, physics, chemistry, statistics, and meteorology as applied to crop production would tend to use the deterministic approach rather than the stochastic approach.

The importance of root media as well as climate on crop yield should be emphasized. For example, in the early 1940's, 100 to 120 pounds of nitrogen per acre were applied on plots that had been planted continuously in corn for 26 years. The average yield had been 26 bu/acre. After application of the nitrogen, yields of over 100 bu/acre were obtained. Parallel results were soon obtained on Illinois prairie soils. Continued experimentation demonstrated that corn could be grown continuously with a gradual increase to yield as much as 135 bu/acre. However, if farmers could not obtain nitrogen for a year, corn yields would probably decrease to 60 to 70 bu/acre. Lack of nitrogen a second year would cause the average yield to be 40 to 50 bu/acre. This decrease in yield would be especially true for the soils that developed under the deciduous hardwood forests of oak, maple, and hickory climax, which predominate in the area east of the Mississippi River. This decrease in yield would be especially noticeable from Indiana to the Atlantic coast if adequate levels of essential elements such as nitrogen were not maintained by applications of commercial fertilizers as necessary. Thus, root media can have as much effect as climate on crop yield.

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PART B

By George W. Robertson[*]

In the near future, crop-weather modeling will become more of a science than it is today. In building these models, two items must be carefully considered. One major consideration is data limitations. In terms of building models for predicting worldwide food production, data will always be limited. In a situation in which worldwide food production falls below population growth, the problem will be trying to predict how much food can be grown for a growing population. Thus, global crop-yield predictions will become more urgent than local crop-yield predictions. However, simple observations, such as daily maximum and minimum temperatures and daily precipitation measurements, will still be used. These observations will be supplemented by data from remote-sensing techniques and satellite platforms.

A second major concern in building models is the real requirement of the model. What is the aim or purpose of the model? Why predict crop yield? What type of model is preferable? The model must be relatively scientific, even though a perfectly deterministic-type model cannot be made. Physics, plant physiology, plant morphology, and plant response to climate must be included in the model. Significant regression coefficients and good predictions can be obtained, but these factors do not indicate what is occurring in the plant or the crop. For example, precipitation is not the moisture that the plant uses; it is the moisture that gets into the soil and is extracted from the soil by the plant. Thus, available soil moisture should be measured rather than rainfall or precipitation. Models exist for estimating soil moisture from simple climatological observations. These models could probably be improved, but one way of managing this type of limited data is to put them in terms of properties that have a direct bearing on plant growth. Also, models should be developed to measure effective plant temperature rather than maximum and minimum temperatures.

In 1953, plant temperature was effectively calculated from simple meteorological observations. The model was then divided into submodels in which the basic data were plugged into some model subsystems, and certain indices were developed. These indices were then related to the final yield. If these numbers are mixed correctly, response functions that are generally characteristic of a plant can be obtained.

Finally, after a model is completed, it must be subjected to a thorough testing to prove that it is better than any other model. Investigators hesitate to compare their models. If the model cannot meet this comparison test, why continue it and saturate the literature with possibly meaningless information? If the models are tested and developed in this manner, then they should be universally applicable to a certain number of crops or family of crops. Actually, the ultimate aim is to have models that are universally useful.

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By H. O. Hartley*

Two points of controversy have arisen. The first controversy seems to occur between advocates of what might be termed the "best scientific model for yield forecasting" as opposed to the development of a "usable model" in terms of presently available forecast technology and predictors. Each model-building advocate is justified within his terms of reference. The scientific approach will examine the dependence of plant physiological phenomenon on climatological, biochemical, and other environmental factors. Present efforts have not as yet achieved the ultimate goal of building such a model. Even if this goal is achieved, the model will contain many factors that must be used as predictors. Many of these factors will not be available on a real-time basis for substitution into the model for the computation of the yield-per-acre figure. In addition to developing such scientific models, it is necessary to develop simpler models known to oversimplify the effect of many variables and concentrate on a workable model equation, which involves only predictors that are available on a real-time basis. Team members working on the two types of models should recognize the limitations and needs of the other team. The scientific model-building activity will indicate the relevance of important predictors (perhaps not presently available on a real-time basis); thus, the imperfect but presently usable models can be improved by pointing up the need for collecting statistical information on relevant predictors needed for an effective model for forecasting yields.

The second controversy that seems to have arisen is between the advocates of so-called "deterministic model building" and "statistical model building." A deterministic model is actually a scientific model or, more precisely, a scientific law in terms of the exact physical sciences. An attempt to build a completely deterministic model in terms of the exact sciences can only be regarded as an idealized abstraction. When predicting biological phenomena, an attempt to build such a model will result in an unmanageable number of variables on which plant growth will depend. Recognizing that many possible variables have to be ignored, scientists using the statistical approach attempt to concentrate on the important variables or important predictors. The variables that are deliberately ignored will be pooled into the statistical error of the prediction model. The statistical model will include important variables or indices — that is, combinations of variables that represent the phenomena most relevant to plant yield. Moreover, a deterministic law is by definition a special case of a statistical law — that is, one in which the variance of the statistical errors is zero. Therefore, a statistical law must be used because it is clearly unmanageable to try to encompass all the variables. Nevertheless, it is vital for the statistician to cooperate with the subject-matter specialists to acquire information concerning relevant variables and predictors.

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To summarize, the statistical model building in which a statistician is working alone is clearly a fallacy. However, the cooperative effort of a statistician with subject-matter specialists can be most effective. The essential condition is that they are capable of working as a team.

FEYERHERM: Suppose that we are going to relate weather data to yield data, that we are going to take the counties of Kansas, and that we have a weather station in each county. Should we take a weather station, make an estimate for that county, and then sum to get an overall estimate, or should we put together the estimates of the weather, obtain one common weather index for the entire state, and estimate the total yield from that common index?

HARTLEY: You probably do not have sufficient data to get a separate equation for each county. However, if you are talking about a group of counties, then I would say that approach is better than summarizing a weather index for a state. Technically, the small-area equation and aggregation is better because it is an easier way to account for possible interactions. However, you do not have sufficient data to properly set up, estimate, and monitor a small-area equation. As in many cases, a compromise must be made. In our model, we suggested that the crop-reporting district would be a good unit.

NEWMAN: I have worked with both the deterministic and statistical models. I think we presently have to depend on the more purely statistical runs simply because we are not far enough advanced in pure science. When this gigantic demand for information occurs in the immediate future, we will have to depend on the purely statistical approach for better decisionmaking. However, in the long term, we will have to use the more purely scientific approach.

CHIN CHOY: I concur with Dr. Robertson's statement about testing models. I would like to see some organization-sponsored testing of each model — statistical, mechanical, or conceptual — to see which model is best.

BURKE: If we are going to build a long-range solution for this particular modeling problem of predicting how much food a biological system (namely, the Earth) is going to produce, we will have to form a tutorial seminar composed of people who know plant physiology, soil mechanics, and so forth. Everybody knows that the solar flux is going to be important. Why is it going to be important? How is it going to be important? How do you predict this aspect of the model? We must get together, not just to talk about our models, but to talk about the basic physics, chemistry, and biology that are involved.

PETERSON: I have never been personally satisfied looking at systems that seem to be random. I have always wanted to find what organization existed in the system beyond that. I feel that what you say is quite correct. In the last year, remote-sensing technology has greatly improved. For example, we can now rectify maps so that a

satellite map is no longer canted 14° off the compass. We can put the map on the compass, and we can rectify it north and south and east and west with less than a 1-percent error. Now this accomplishment is a tremendous advantage to someone who has been working in land use and soil classification. Moreover, we have been able to register the maps so that an overlay technique can be used. The specificity of the resolving power is surprisingly good for an altitude up to 560 miles; thus, the potential of remote sensing is very great.

BARNETT: We will have to use various satellite data to predict yields accurately over large areas. We should probably use a parameter such as the scanning radiometer radiances from the National Oceanic and Atmospheric Administration satellite. The problem with this parameter is that, in converting it to surface temperature, atmospheric effects are obtained. Thus, we have been hoping to use the vertical temperature profile radiometer (VTPR) to correct the scanning radiometer to attain the surface temperature. Use of scanning radiometer temperatures and one or two channels of the VTPR might be preferable because the scanning radiometer values would be a function of both surface temperature and atmosphere, whereas the VTPR measurements would be a function only of atmosphere. We would like to predict rainfall from cloud amounts, and, if another parameter exists in there, we would like to find a function of that parameter. Thus, we may not want to use the traditional parameters in our yield models.

BARGER: One topic that my colleagues and I discussed was setting a potential yield and then downgrading that yield by evaluating detrimental factors. The cumulative environmental effect can be measured during the growth and reproduction period. In that respect, duration of detrimental effects and the magnitude of the effects of such a period are important. For example, a 6-week drought is more serious than two separate 3-week droughts. This problem can be solved in the curvilinear aspects of the equation. However, we need to be sure that we recognize this cumulative nature of plant response and then reduce the potential yield by other influences such as pest and disease effects, fertilizer shortages, and cataclysmic environmental occurrences (freezes, hot winds, and so forth). More variability occurs in measuring soil moisture than in estimating it because nothing is more heterogeneous than summer rainfall distribution melded with the kinds of mixed soils produced by glaciation, for example. Also, soil moisture sampling is prohibitive; thus, it is fortunate we can estimate quite well from weather data. We had better keep our rain gages out and our temperature shelters open for another reason — that is, to attain some calibration and ground-truth data. The areal averaging capability of remote sensing of surface conditions cannot be overestimated, but obtaining unbiased estimates also requires ground truth. As we learn more about the measurement of leaf area, rate

of plant development, and stage of plant development, we will begin to recognize from the satellite data the stages or rates of plant development and, eventually, the yield potential. However, for the immediate future, we must rely largely on point weather observations.

PITTS: We have seen many types of models emerge in radiative transfer because many investigators do not like to compare their model with other types of models to see which model is best. The same problem is apparent in crop modeling. In addition to testing these models under the same conditions where they are applicable, we should test these models by returning to the physics of the plant, which would be an extremely difficult but worthwhile approach. The physiological models, developed by this approach, will be able to predict crop response to a much wider set of environmental conditions than a statistical model using many decades of field data. Because of the complexity of these models, they would be prohibitively expensive to operate on a large scale but could be used as an input to simpler regression models which have the desired responses and accuracy and yet are economical and timely to operate. Likewise, in remote sensing, we must use these physiological models and integrate them with the plant canopy reflectance models. If we use the direct measurement of yield by remote sensing, we will have to integrate that measurement of yield with measurements of yield using the conventional meteorological data. Interfacing two yield estimates is going to be very difficult. However, if these physiological models are properly set up, the integration process will be somewhat less complicated.